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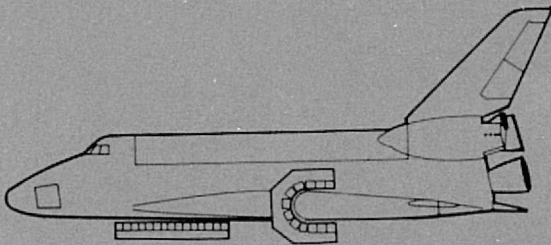
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JSC 09490
NAS9-14041
DRL T-1009
DRD 463
AND MA 451T

NASA CR-

144-390



A LEADING EDGE HEATING ARRAY

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AND

A FLAT SURFACE HEATING ARRAY

FINAL DESIGN AND FINAL REPORT



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W. J. ...
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A LEADING EDGE HEATING ARRAY AND A FLAT SURFACE HEATING ARRAY

FINAL DESIGN AND FINAL REPORT

10 JULY 1975

REPORT MDC E1232
JSC 09490

26 JUNE 1974 TO 10 JULY 1975

SUBMITTED TO NASA/JSC
UNDER CONTRACT NAS 9-14041

DRL T-1009
DRD SE 463 TB
AND MA 451T

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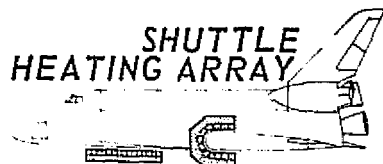
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CORPORATION

**FINAL REPORT****FOREWORD**

This Final Design and Final Report was prepared by McDonnell Douglas Astronautics Company - East (MDAC-E) for NASA-JSC Contract NAS9-14041, A Leading Edge Heating Array and a Flat Surface Heating Array. It covers the period 26 June 1974 to 10 July 1975. This effort was performed for the National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, under the direction of the Engineering Division with Mr. J. C. Welch as the Contract Technical Monitor and Mr. W. D. Sherborne as the coordinator for the Structures and Mechanics Division. Mr. H. E. Christensen was the Program Manager and Mr. B. G. Cox was the Deputy Program Manager for MDAC-East.

**FINAL REPORT**DISTRIBUTION LIST

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**FINAL REPORT****ABSTRACT**

This report describes accomplishments made by MDAC-E in the fabrication, acceptance testing and delivery of a heating array for testing full-scale sections of the leading edge and lower fuselage surfaces of the Shuttle. The work described herein was the culmination of design and development activities initiated under Contract NAS9-13091 (Phase I) and expanded under NAS9-13544 (Phase Ia). The heating array was designed to provide NASA a tool for development and acceptance testing of; leading edge segments (up to 60 inches long and with variable edge radius as small as 3.4 inch) and large flat sections (4 x 8 feet) of the main body thermal protection system.

The array was designed using a variable length (72 inch/48 inch) module concept to meet test requirements using interchangeable components from one test configuration in another configuration. Heat generating (strip graphite element) modules and heat absorbing modules were employed to achieve the thermal gradient around the leading edge. A support was designed to hold the modules to form an envelope around a variety of leading edges. In addition to providing structural support to each module the structure also supplies coolant to each module. The support structure was designed to also hold the modules in the flat surface heater configuration. An optical pyrometer system mounted within the array was designed to monitor specimen surface temperatures without altering the test article's surface.

The array was fabricated per engineering drawings, components were functionally checked (including operating heater modules at 3200°F for ten minutes), and the array assembled before disassembly for shipment to NASA for installation in JSC's 10 foot diameter vacuum chamber.



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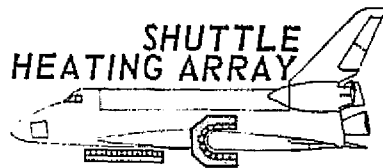
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1.0 INTRODUCTION

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1.0 INTRODUCTION

Development and qualification testing of full scale leading edges and flat surface panels for the Space Shuttle's Thermal Protection System (TPS) is a necessary milestone in the Shuttle program. We at McDonnell Douglas Corporation (MDC) have been involved in the design, analysis and development of heat protection for Shuttle and have an awareness and ability to conduct the necessary kinds of environmental tests. A significant technology base has been established by our teammates. One facet of this technology is mission simulation testing which includes radiant heating of thermal protection systems under real time flight conditions from the cold, near vacuum of space through peak entry heating and post flight heat soak. The need for testing leading edges on Shuttle was identified and a modular heater concept was developed by MDC under Contracts NAS 9-13091 and NAS 9-13544. The selected modular concept permits efficient placement of heater modules for testing various radius leading edges. This arrangement maintains uniform heating of the test article in the spanwise direction while providing a means of varying the heating environment in the chordwise direction through individual control of the heater modules.

The graphite heater system described herein was developed to overcome several problems that exist with tungsten filament quartz lamps. When operated at high temperatures and/or heat fluxes, quartz lamps have a relatively short life, are expensive to replace, arc over at low pressure due to the high operating voltages, and require high density installation to achieve the required high heat flux, which in turn causes over-temperature of the quartz envelope. The graphite heater system has low cost graphite elements, which have a long life, are simple to replace, and which operate at low pressure as well as pressures in excess of one atmosphere. High heat flux density is inherently attained by the nature of the heater element design.

The upper surface of the leading edge experiences the low convective heating of lee side flow. The upper surface also receives significant cross radiation from the hot lower surface of the leading edge and hence will reject heat to space by radiation. Absorber modules were designed for the leading edge heating array to accommodate this heat rejection. These units replace heater modules in those regions around the leading edge where heat rejection occurs due to internal heat transfer. Figure 1 shows a leading edge test configuration, eight 72 inch heater modules and seven 72 inch absorber modules.

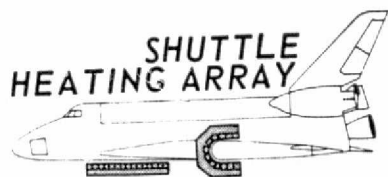
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Design features are incorporated into some components of the leading edge array which permits using those components to form a large flat surface heating array. Heater modules in addition to those required for the leading edge array were supplied so that a flat surface heater can be assembled with a heated area up to 4 x 8 feet. Figure 2 shows two flat surface configurations, twelve 72 inch heater modules and ten 48 inch heater modules.

A support structure is supplied which can be used to support the heater and/or absorber modules in either the leading edge or flat surface configuration. The heater support structure was designed to fit within the available envelope of a 10-ft diameter test chamber located in Building 260 at NASA-JSC, and interface with the necessary utilities within the chamber.

Each heater and absorber has provisions to mount special optical pyrometer assemblies, developed under Contract NAS9-13544, to sense the surface temperatures of test articles without altering the surface of the test article.

As the heating array is described in more detail in the following paragraphs, the flexibility of the heating units will become apparent. The heater modules can be arranged to conform to contoured surfaces with a radius as small as 3.4 inches as well as being arranged to form large flat heating arrays to test High Temperature Surface Insulation (HRSI) or other TPS panels. Although the heating array was designed specifically with Space Shuttle in mind, the flexibility that has been designed into the array will allow it to be utilized for a variety of test programs.



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HEATING ARRAY - LEADING EDGE CONFIGURATION

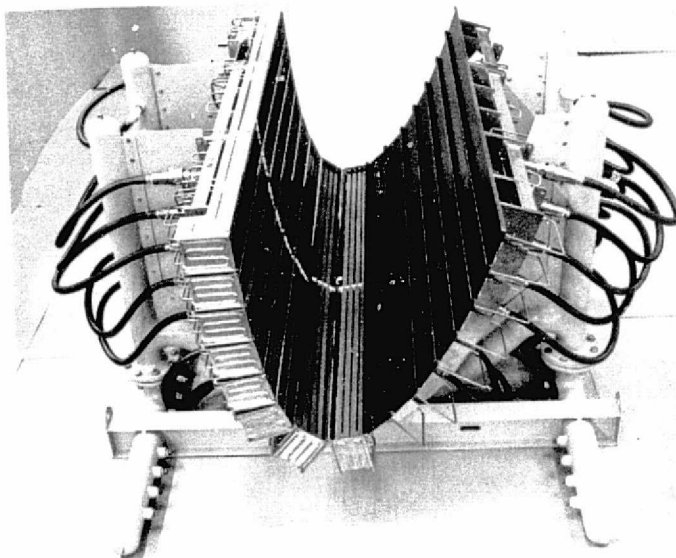


FIGURE 1

HEATING ARRAY- FLAT SURFACE CONFIGURATION

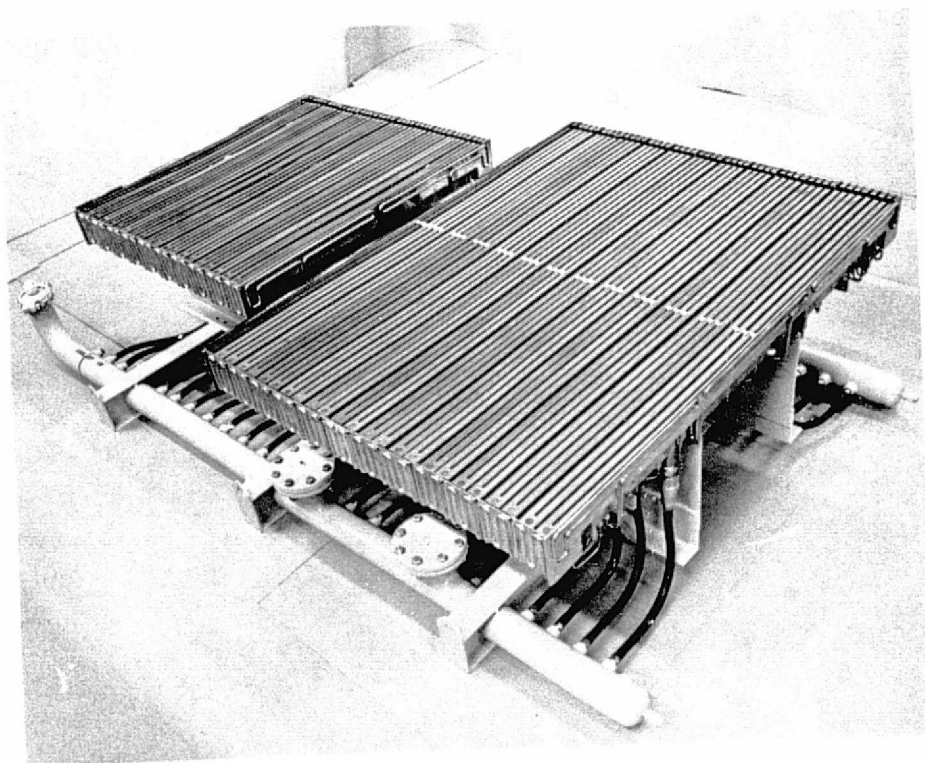
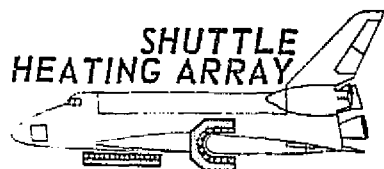


FIGURE 2



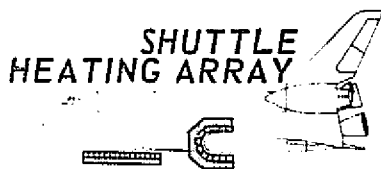
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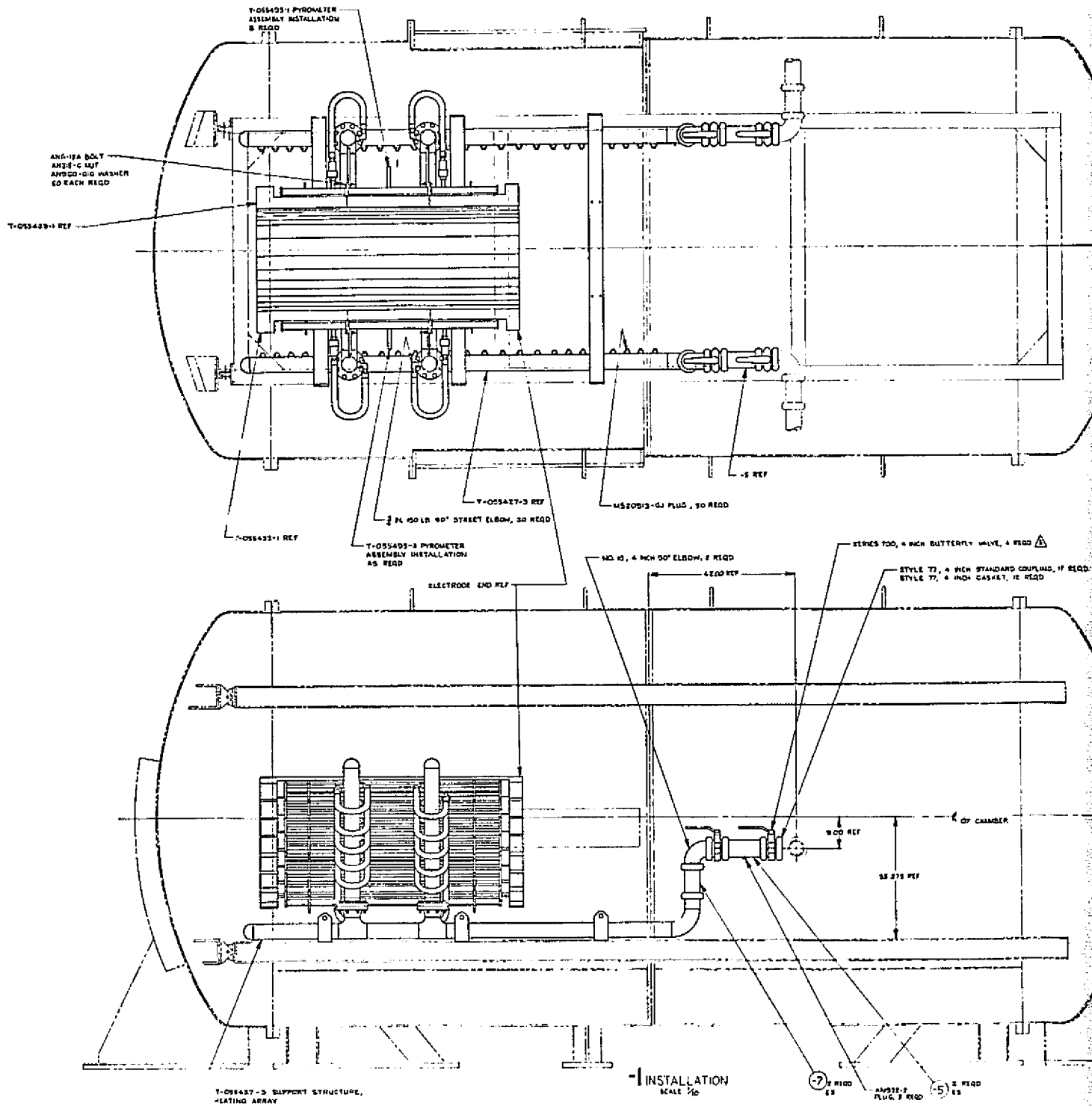
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2.0 SUMMARY

**FINAL REPORT****2.0 SUMMARY**

A large graphite radiant heating array was designed and fabricated for testing of full scale leading edges and flat surface panels for the thermal protection system of Space Shuttle. The heart of the system is the basic heater module which is designed in three sections so that it can be used in a 48-inch length, or a 72 inch length, by the removal or addition of the center section. A similar three-section assembly called an absorber, is used where heat rejection is required. The leading edge array consists of eight 72-inch heaters and seven 72-inch absorbers, arranged in a leading edge shaped configuration. The flat array support structure will accommodate up to twenty four 72-inch heaters or any combination of 48-inch or 72-inch heaters. Each heater module is equipped with an optical pyrometer assembly for sensing the test article's surface temperature. The final design of the heating array evolved from a combined analytical and prototype testing approach. The design philosophy employed a minimum and maximum approach, where durability and reliability were maximized and complexity and exotic materials minimized. Because of its inherent flexibility and versatility, the array was designed for a long life including such things as plating carbon steel parts to prevent corrosion and rust contamination. Continuous coordination with NASA-JSC resulted in a design that was essentially integral with the 10 ft diameter vacuum chamber in Bldg. 260 at NASA-JSC. Figures 3 and 4 show the array mounted in the chamber and illustrate the convenient interfaces as well as how the array fits on the existing drawer assembly of the chamber. An extensive thermal analysis was made along with supporting calculations to determine the cooling water requirements and the electrical power requirements. The thermal analysis sized the width of each module at approximately 5 inches to satisfy the spatial heat flux profile, while the length was specified at 72 inches to satisfy the 85% heat flux uniformity requirement over the 60 inch leading edge test article. Location of heater modules and absorbers, along with heater power and element temperature, were also calculated by the thermal program. A development test setup was assembled including a 72 inch preproduction heater assembly and a 72 inch test article, for the purpose of supporting the analysis and confirming the design concepts. The tests run with this setup included coolant flow distribution tests, maximum temperature tests at test article temperatures above 3200°F and measurement of the heat flux uniformity at each end of the 72 inch heater assembly. Close coordination of the test results

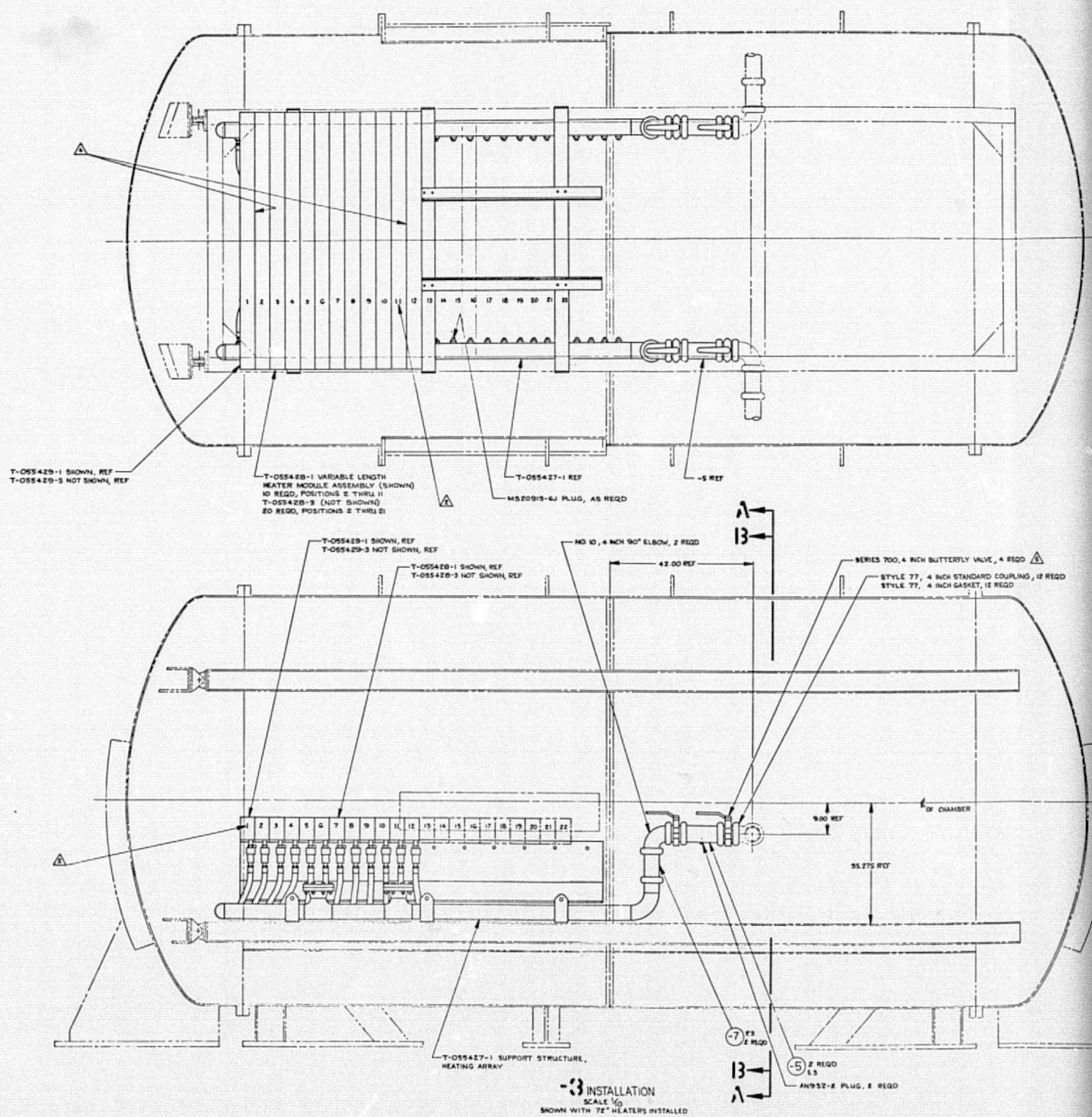
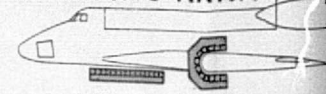
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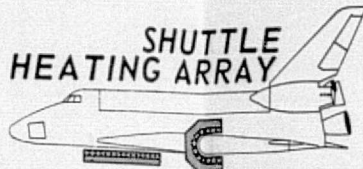
FOLDOUT FRAME /

MCDONNELL D

INSTALLATION OF LEADING EDGE HEATING ARRAY



FOLDOUT FRAME



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INSTALLATION OF FLAT SURFACE HEATING ARRAY

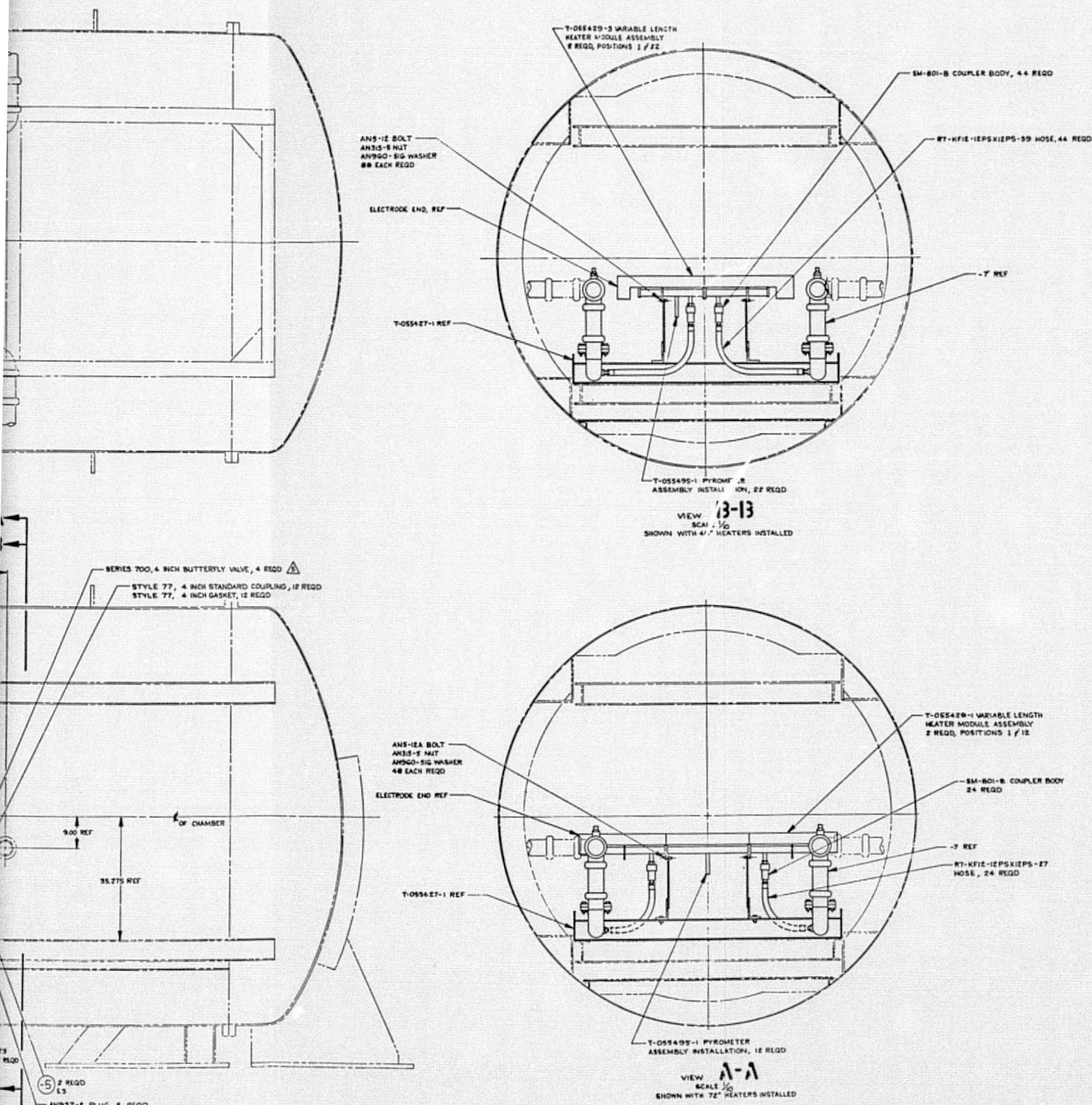
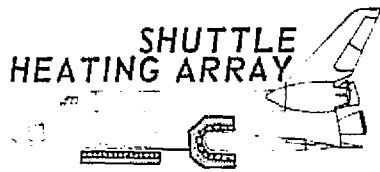
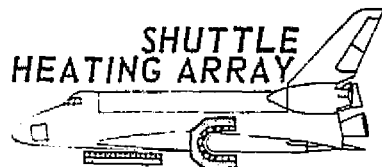


FIGURE 3

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with the analytical program insured a high confidence level in the design. Further testing included operation of both the 48 inch and 72 inch heaters on their side and heater operation at low pressures from 0.5 torr to 100 torr to insure freedom from arcing. Concurrent with the analytical work and the development testing, the module and array design was finalized and ultimately fabrication began. Machining, welding and assembly jigs and other associated tooling were used to insure the interchangeability of parts. After fabrication, each heater module was subjected to an operational checkout in our heater facility prior to shipping the unit to NASA-JSC. This checkout demonstrated that each unit was functionally operational and capable of achieving and operating at these temperatures. Each production module received a pressure leak check, an insulation leakage resistance test, a high voltage breakdown test, a leak test in vacuum, a water flow rate test, and an operational checkout. The fact that the performance of each of the production modules was virtually identical, fortified our approach of careful design and patient attention to detail in the fabrication. Two 72 inch heater modules were also installed on the support structure and operated as a unit to demonstrate the performance of the array at the 3200^oF design condition. The entire array was also assembled in the leading edge and in the flat configurations to insure proper interface between modules and the support structure. All of these activities were performed to provide a quality heating array to NASA for testing and evaluating the thermal protection system for the Space Shuttle.



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3.0 DESCRIPTION OF HEATING ARRAY SYSTEM



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3.0 DESCRIPTION OF HEATING ARRAY SYSTEM

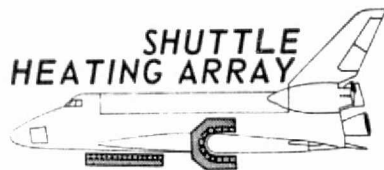
The individual components of the heating array are described in the following paragraphs. Design features incorporated in the units provide convenience, utility, versatility, and effectiveness. The components include a variable length heater module, a variable length absorber module, a support structure to support these modules around a leading edge test article and in a flat array, and optical pyrometers for measuring test article surface temperatures.

3.1 VARIABLE LENGTH HEATER MODULE - The variable length heater module shown in Figure 5 consists of three sections; the electrode end, the expansion end, and a center section which can be removed to vary the heater length from 72 to 48 inches. This design feature provides an efficient method of testing various size test panels where an array formed of 48 inch heater modules will provide the necessary heat flux uniformity. Both the 48 inch heater module configuration and the 72 inch configuration are shown in Figure 6.

Figure 7 is a layout of the heater module in the 72 inch and 48 inch configurations. The heater is approximately 5 inches wide by 75 inches long in the 72 inch configuration and contains two two-pass serpentine graphite heater elements. Each pass has constant cross-sectional dimensions throughout the heated length of 0.8 inch wide by 0.42 inch thick. Both ends are thickened to 0.75 inch for the electrical power connections and end supports.

The structural backbone of the heater is formed by two rectangular coolant manifold tubes. These tubes have gasketed, flanged ends and the end heater sections can be bolted together without the center section to form the 48 inch heater configuration. These parts are electroless nickel plated for corrosion protection. A no-spill quick disconnect coupler is provided, one in each end section for the coolant supply and return. The center section receives coolant automatically when installed between the two end sections. All of the heater components are supplied coolant from these manifold tubes. Coolant flow rates to a 72 and 48 inch heater is approximately 24 and 18 gpm respectively with a 60 psi pressure drop (ΔP). Each heater module is equipped with a coolant interlock flow switch.

Mounting flanges are welded to the heater module coolant manifold tubes. The heater is supported from the two flanges extending from the center heater section when the heater is in the 72-inch configuration, and from the two flanges on each end section when in the 48-inch configuration. With this arrangement either heater configuration can be mounted on the array support plates without altering the spacing between the plates.



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VARIABLE LENGTH HEATER MODULE (72-INCH CONFIGURATION)

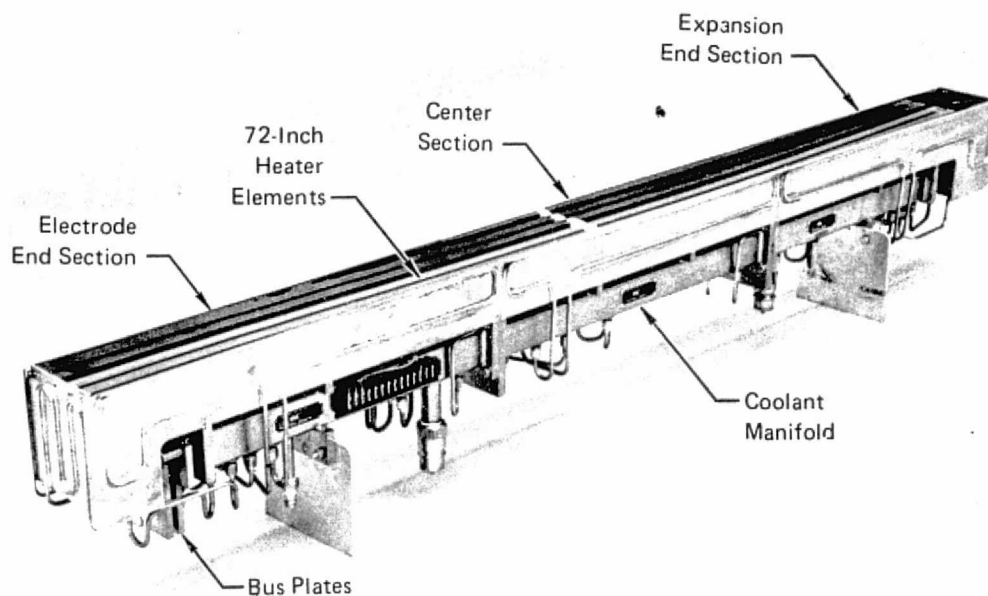
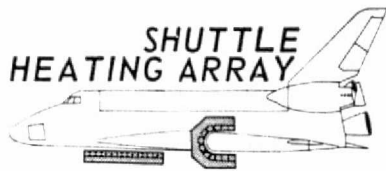
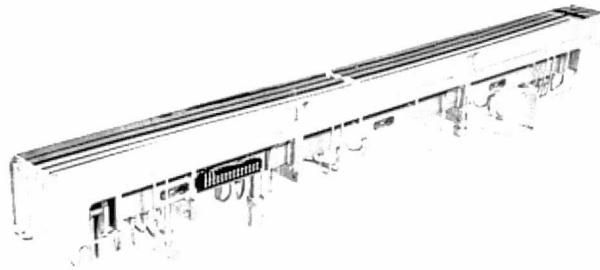


FIGURE 5



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VARIABLE LENGTH HEATER MODULE 48 INCH CONFIGURATION



72 INCH CONFIGURATION

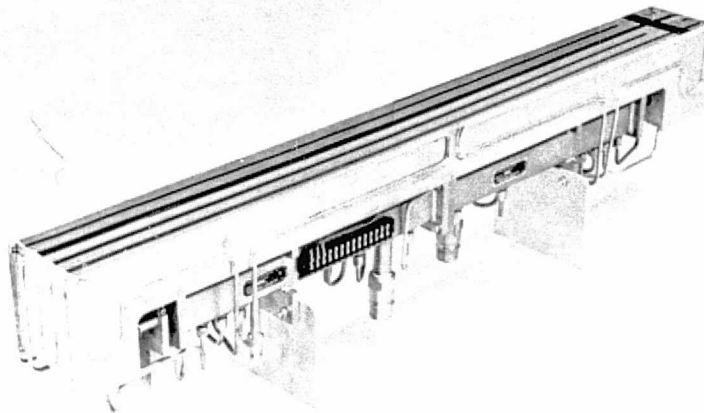
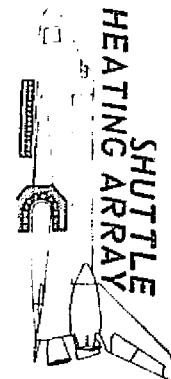


FIGURE 6

VARIABLE LENGTH HEATER MODULE ASSEMBLIES



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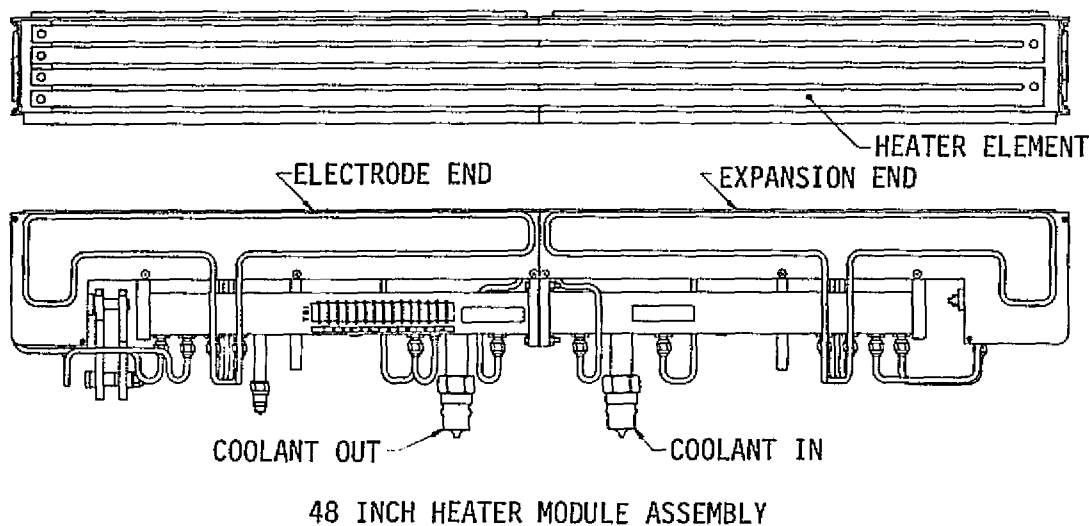
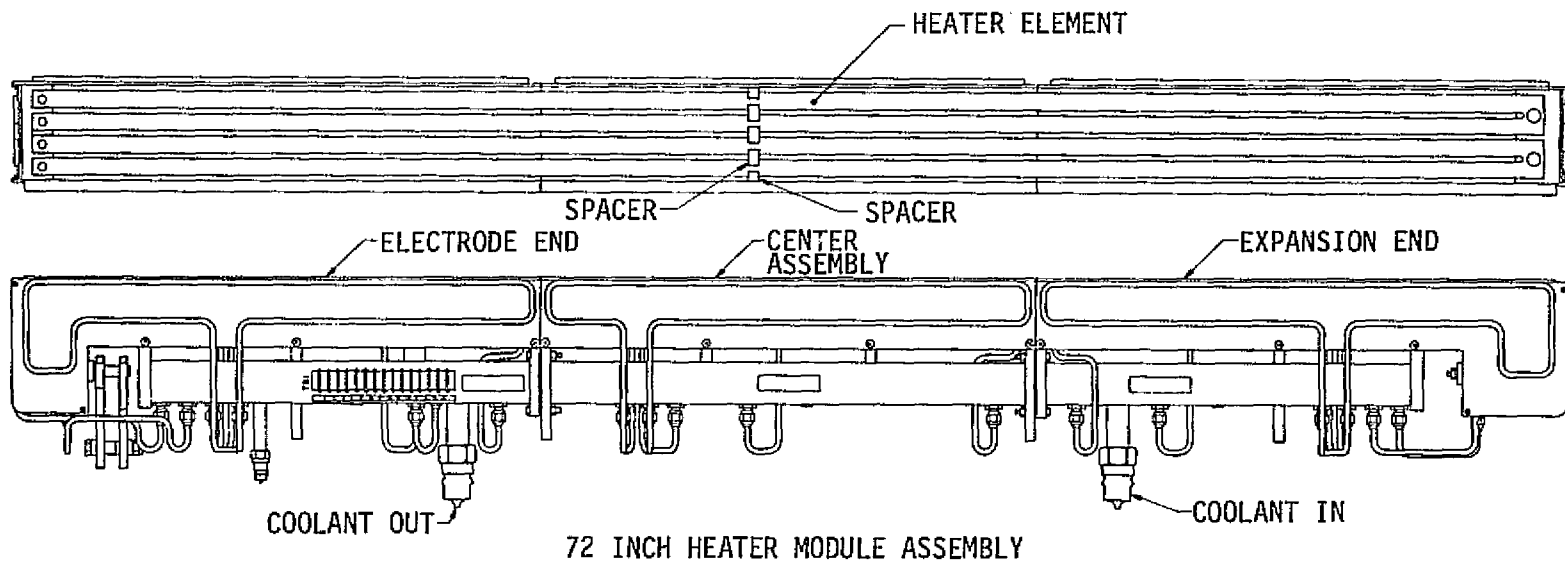


FIGURE 7

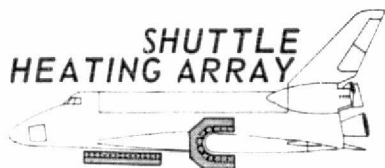
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The Electrode End Assembly is shown in Figure 8 and its details are shown in Figure 9. Water-cooled copper tapered pegs brazed into brass end blocks retain one end of the heater elements and transmit power to the element. This tapered peg mounting feature retains the element through friction and provides positive electrical contact between the graphite and the copper peg. Two tapered pegs in the center end block make a common connection between the two elements. Copper electrode rods are brazed into sockets in each end block. These rods pass through the brass end manifold, and copper bus plates (terminals) are clamped to the rod ends. The end blocks and rods are electrically insulated from the heater structure by ceramic insulators and phenolic sleeves. O-rings fitted in grooves seal the water passages between the components. A constant clamping force is exerted on the O-ring seals by a wave spring washer held in place with a snap retaining ring.

Figure 10 shows the bus plate details and how they attach to the electrode rods. The two bus plates connect the heater elements in parallel and supply the two connecting points for power leads. One bus plate attaches to the outside electrode rods, and the other attaches to the center electrode rod. This rod is common to the two middle copper tapered pegs. The bus plate assemblies have been designed to accommodate two conductor water-cooled power cables with Flex Lo-X Type 12S terminals manufactured by Flex-Cable Corp. If this type of power lead is used, the power lead end connection is placed between the two bus plates and clamped up with the insulated bolt to provide electrical contact to each of the two conductors.

The Expansion End Assembly is shown in Figure 11 and its details in Figure 12. This assembly is designed to support the end of the heating element, and take up thermal expansion of the heating element during operation. It consists of a graphite lever pinned at the bottom to the water cooled brass end block through a protruding ear. The upper end of the lever is tapered to accept the heating element. This design feature effectively fixes the expansion end of the heating element, and combined with the electrode end design prevents excessive sag in the element. As the element expands during heater operations, the lever arm pivots and provides additional moment on the element and reduces the sag at the center of the element. As on the electrode end, the electrical insulation is provided by a ceramic insulator between the end block and the water manifold and a phenolic sleeve and washer around the clamping stud. O-rings seal the water passages between components.

Water-cooled reflector panels surround the heated zone on five sides leaving only the area above the elements open for radiating to the test article. The



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ELECTRODE END

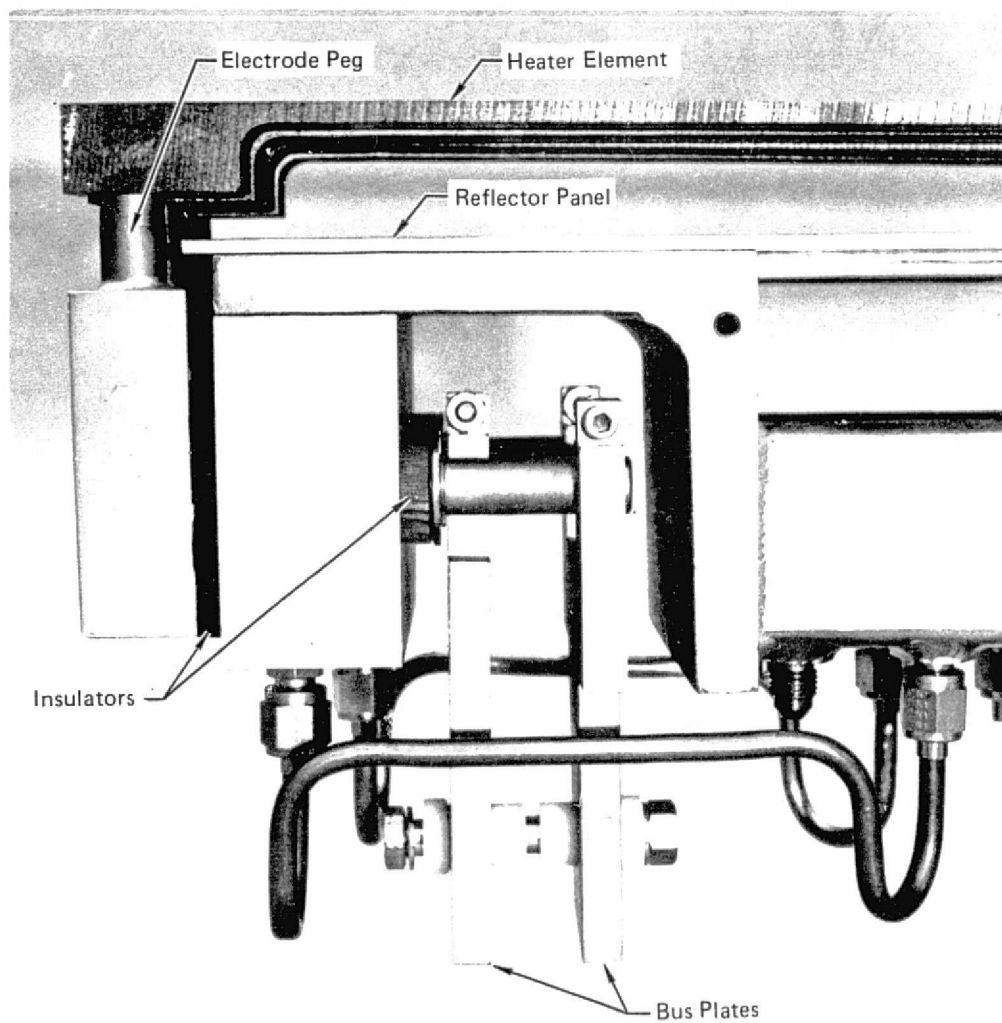
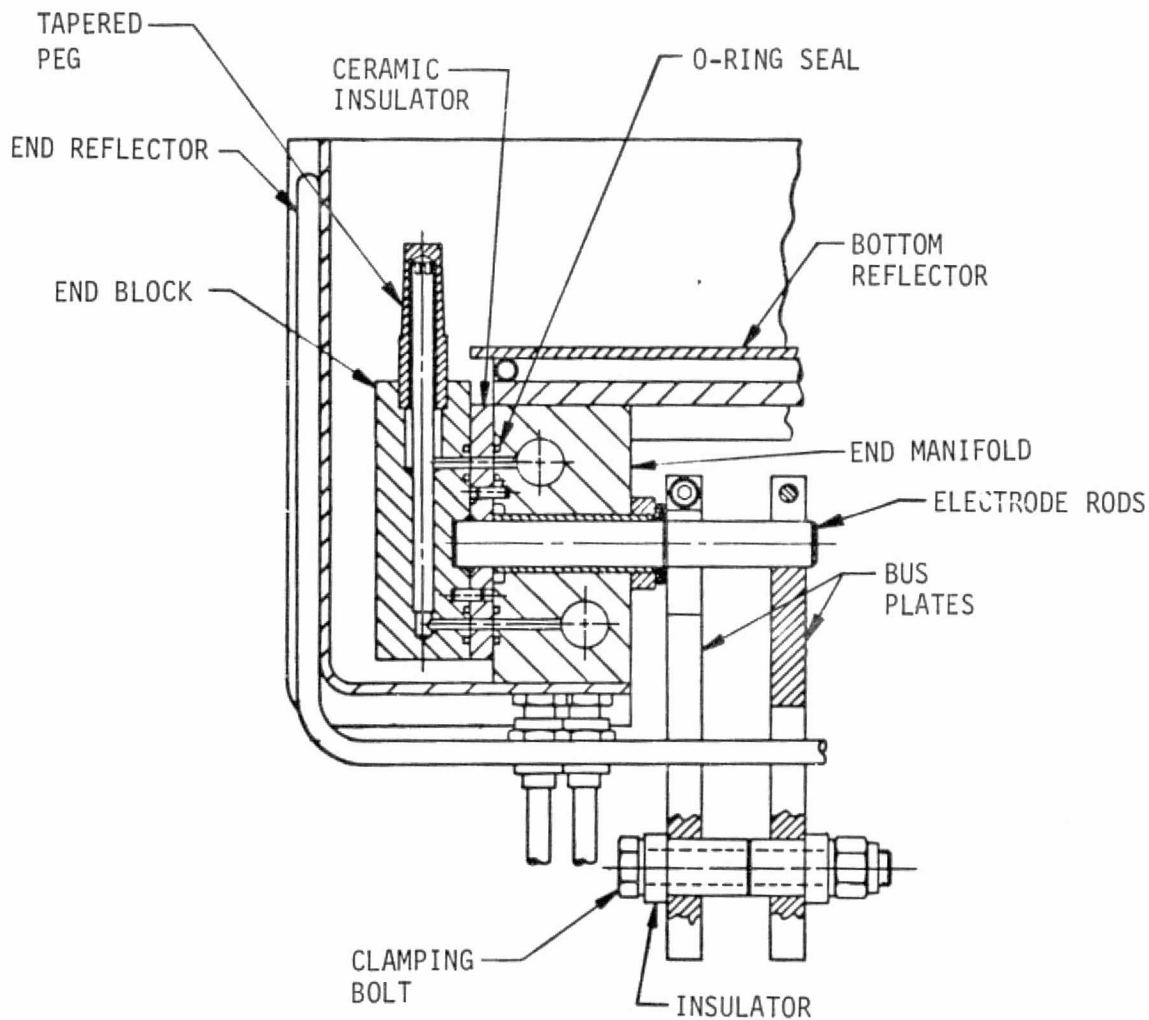


FIGURE 8



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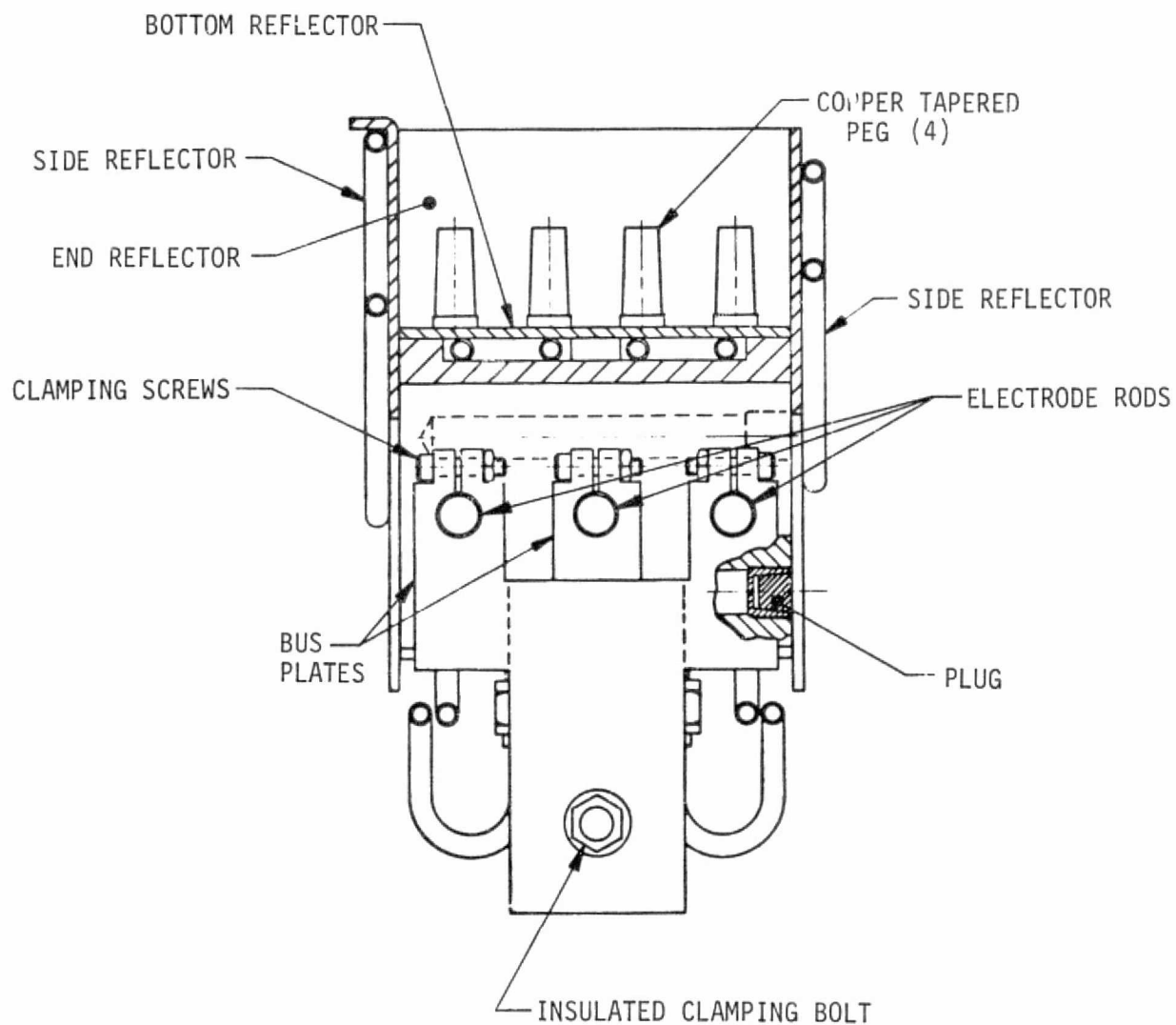
ELECTRODE END ASSEMBLY DESIGN DETAILS





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ELECTRODE END ASSEMBLY
BUS PLATE DETAILS



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EXPANSION END

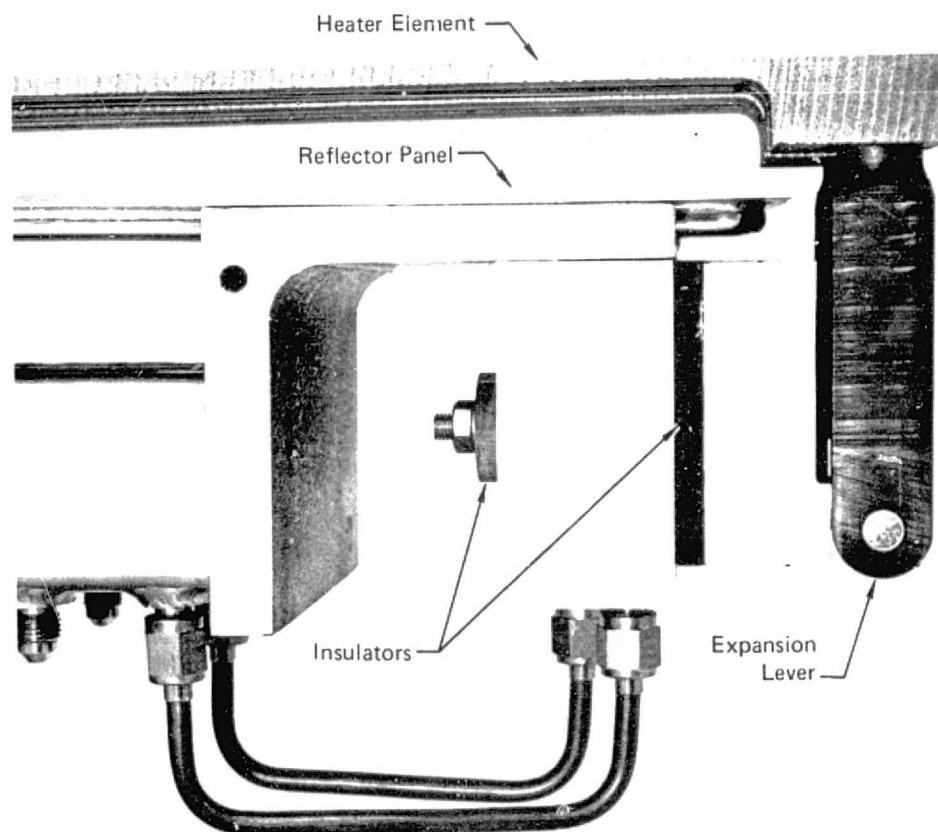
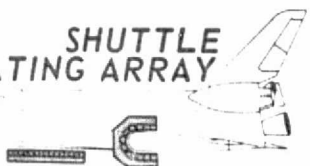
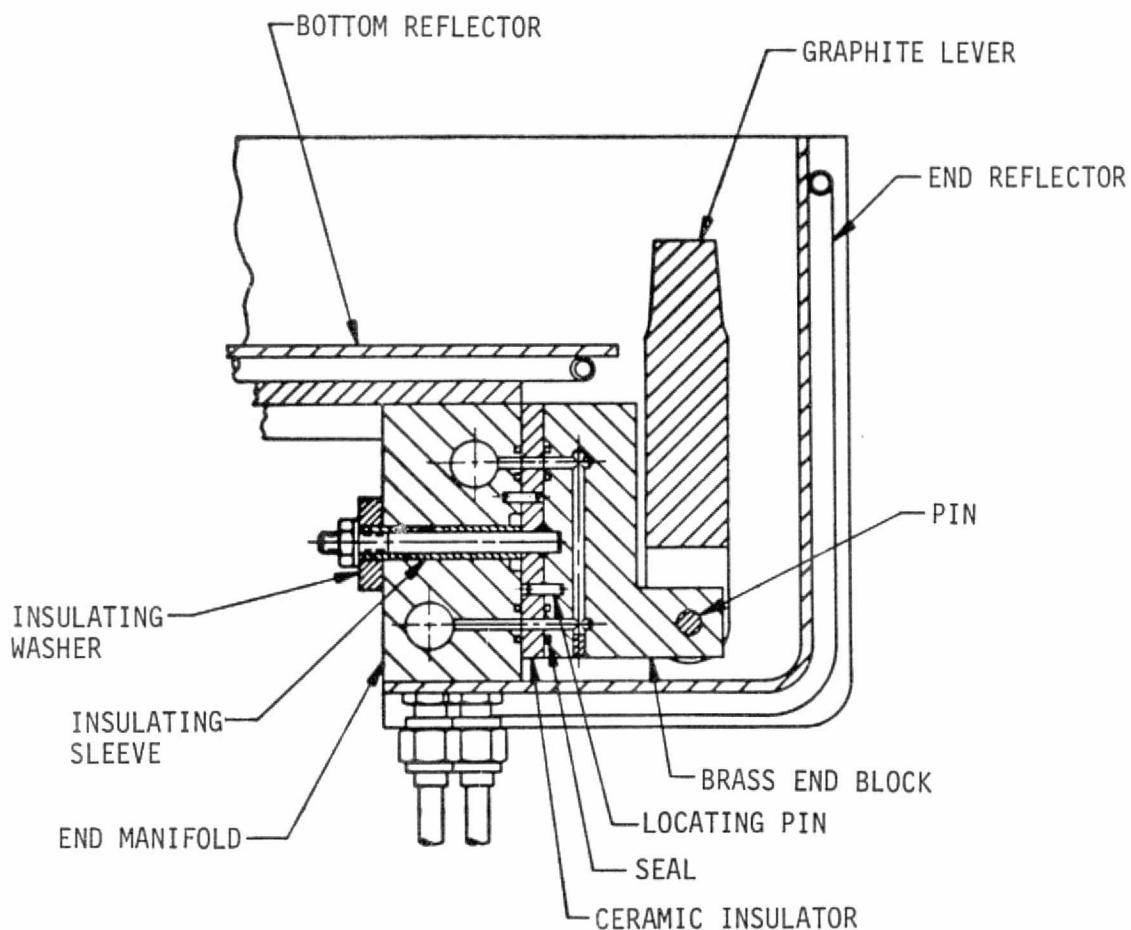


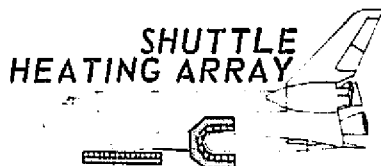
FIGURE 11



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EXPANSION END ASSEMBLY DESIGN DETAILS





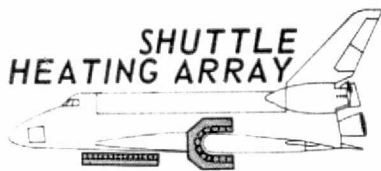
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surfaces of the reflector panels facing the heater elements are gold plated to give a high spectral reflectance which provides efficient operation and enhances the heat flux uniformity. Coolant circuits are attached to the outer surfaces of the reflector panels to remove absorbed energy. The coolant circuits on the side reflector panels are so situated that they nest with the circuits of an adjacent module in the array. This reduces the unheated area between heater modules. One side of the reflectors has a lip which overlaps the adjacent reflector and prevents stray radiation from escaping.

Provision is made in the bottom reflector of each section of the heater to mount an optical pyrometer for measuring test article surface temperatures. The mounting block is fixed to the bottom reflector and automatically aims the pyrometer to look between the heater elements at the specimen surface. The mounting block is water-cooled and prevents overheating of the pyrometer detector. This allows the pyrometer to be removed or installed without breaking coolant connections. Gold plated brass plugs are supplied to plug all pyrometer mounting blocks not in use.

The side reflector panels of the heater module can be removed if desired so that modules can be butted side to side to form a flat heating array. When a large number of modules are so arranged, the modules at the edges of the array have the outermost side reflectors installed to prevent stray radiation from escaping.

3.2 VARIABLE LENGTH ABSORBER MODULE - The variable length concept is carried through to the absorber module. The absorber is shown in Figure 13. It also consists of three sections with the center section removable to shorten the overall length of the unit (See Figure 14). The overall dimensions of the absorber are approximately the same as the 72 inch heater module. The coolant manifolds also form the structural backbone of the absorber and supply coolant to the module components. A water-cooled energy absorbing panel is mounted on each section of the absorber. This panel is contoured at the edges to assume the same shape as the side reflectors of a heater module. The absorber module is thus interchangeable with a heater module in an array where the heater module is being utilized with the side reflectors attached. Any desired coating can be applied to the surface of these panels to obtain the desired emittance characteristics. As with the heater modules, each absorber module panel is equipped with a water-cooled mounting block for an optical pyrometer.



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VARIABLE LENGTH ABSORBER MODULE (72-INCH CONFIGURATION)

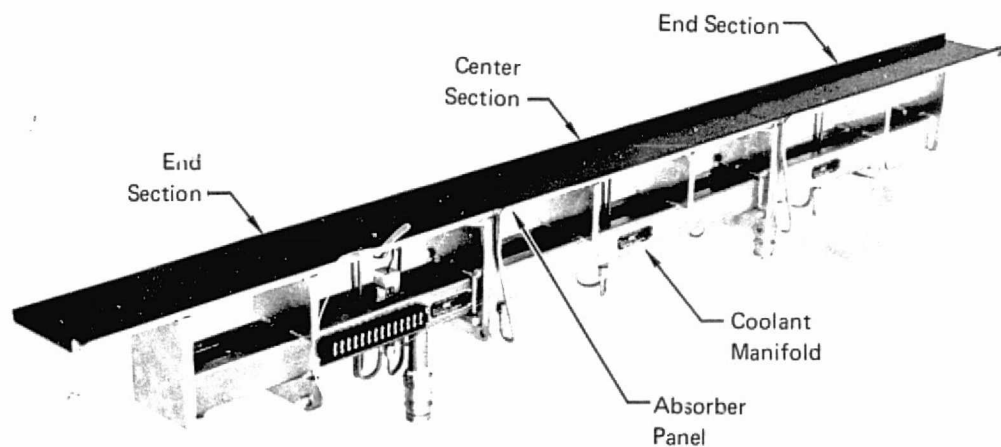
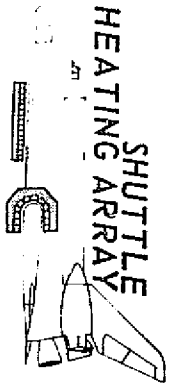


FIGURE 13

VARIABLE LENGTH ABSORBER MODULE ASSEMBLIES

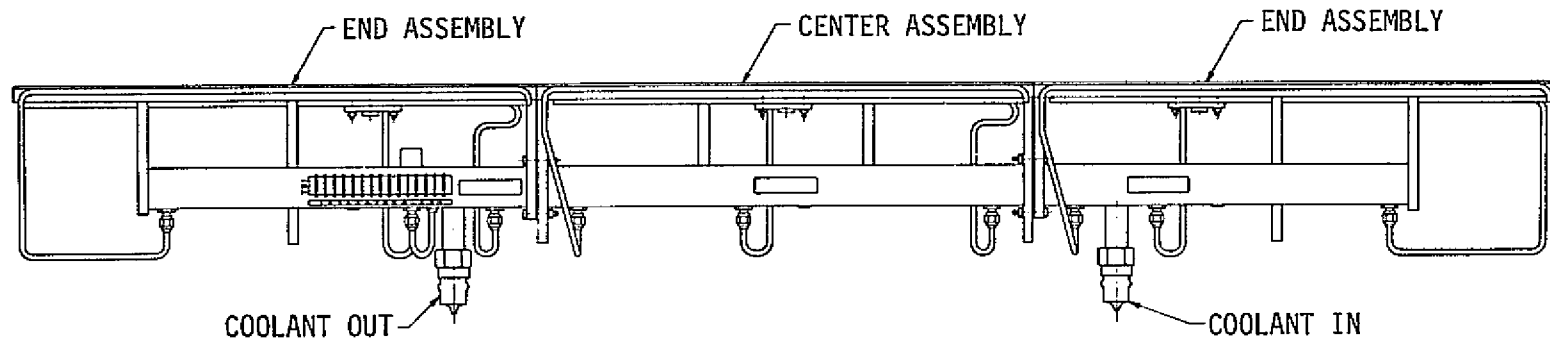


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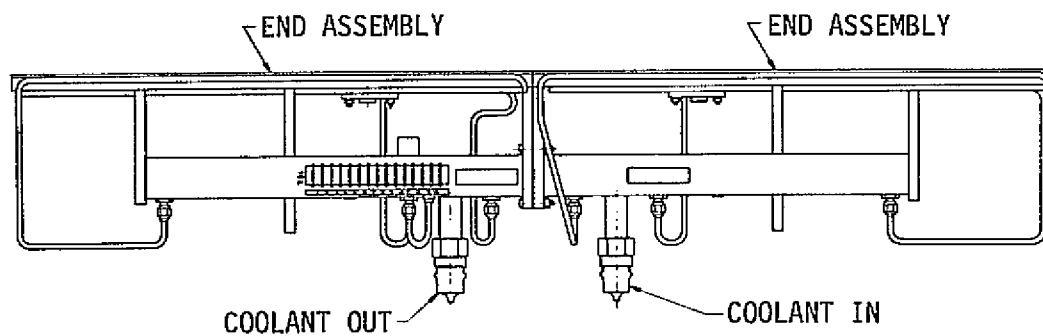
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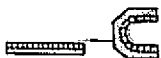
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72 INCH ABSORBER MODULE ASSEMBLY



48 INCH ABSORBER MODULE ASSEMBLY



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The absorber module mounting flanges and spacing are the same as those for the heater module. The coolant flow rates that can be expected for a 72 inch absorber module is 7 gpm at 60 psi ΔP . As with the heater modules, quick-disconnect no-spill couplers are provided on each end section of the absorber for coolant supply and return hoses. Each absorber module is equipped with a coolant interlock flow switch. Figure 14 shows an absorber module in the 72 and 48 inch configuration.

3.3 OPTICAL PYROMETER ASSEMBLY - Optical pyrometer assemblies are provided to indicate the specimen surface temperatures above 2000°F. These pyrometers give the test conductor a means of reliably monitoring the test article's surface temperature. They were developed especially for use with graphite radiant heaters. These pyrometers were fabricated by Thermogage Incorporated, of Frostburg, Maryland, to MDC specifications. The optical pyrometer is shown in Figure 15. It uses a silicon photovoltaic cell having a spectral response from wavelengths of about 0.35 to 1.10 microns with peak sensitivity at 0.83 micron. A lens and field stop define the amount of light reaching the silicon cell from the specimen. The pyrometer indicates the temperature of an area on the specimen about 0.07 inch in diameter at a specimen to heater element distance of 1.5 inches. Additional apertures between the lens and the pyrometer snout reduce the amount of stray light reaching the cell. The focal plane location of the installed instrument and these apertures combine to effectively eliminate any effect of radiation from the heater element on specimen surface temperature indication.

The pyrometer provides a nominal DC output of 0 to 50 millivolts for a black-body specimen temperature from 2000°F to 3500°F. All pyrometer assemblies were calibrated by the McDonnell Standards Laboratory over the temperature range of 2000°F to 3400°F. Based on radiation theory an exponential function was least squares fitted through the calibration data for each pyrometer. The resulting function has the following form:

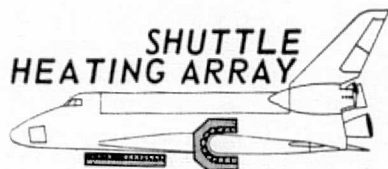
$$T = \left[\frac{B}{C - \ln \left[\frac{V_o}{\epsilon} \right]} \right] - 460$$

where: T = Temperature, °F

V_o = Pyrometer output, millivolts

ϵ = Surface emissivity

B, C = Constants



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OPTICAL PYROMETER ASSEMBLY

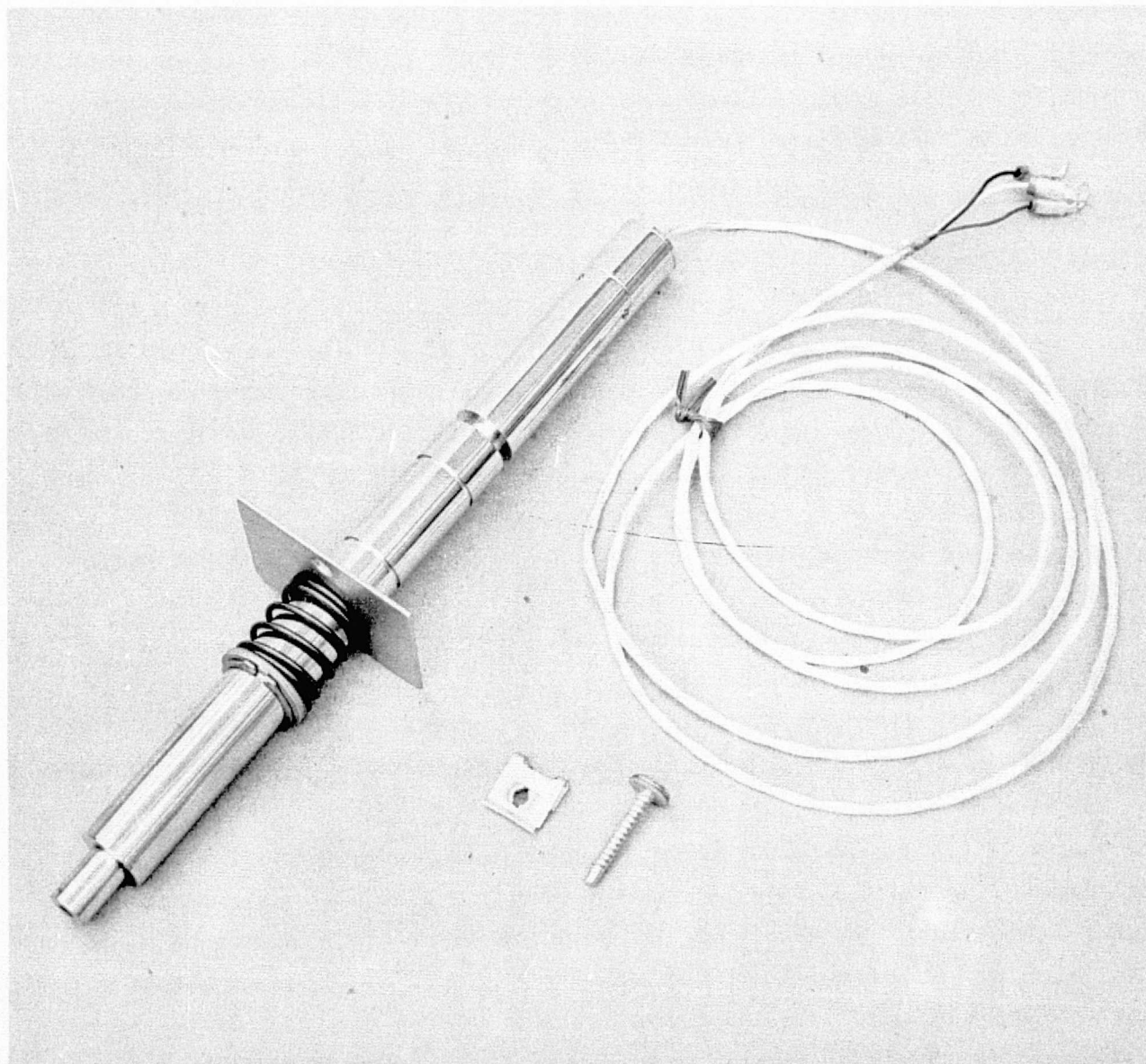
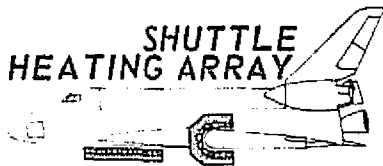


FIGURE 15

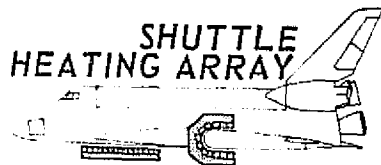
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The values of the constants for each pyrometer are given in Figure 16.

Three alternate mounting locations are provided in each 72 inch heater or absorber module so that the optical pyrometer can be easily installed to view a representative part of the specimen surface. A water cooled mounting block at each location provides support for the nose of the pyrometer and provides sufficient conductive cooling so that no additional cooling connections to the pyrometer itself are necessary. This mounting block also automatically aims the pyrometer upon installation so that it views the specimen surface between the gaps of the heating elements. A spring-loaded mounting plate is attached to the pyrometer body by snap rings. This mounting plate is joined to the heater or absorber module coolant manifolds by a screw.

3.4 HEATING ARRAY SUPPORT STRUCTURE AND OPERATIONAL CONFIGURATIONS - The heating array support structure can be converted to support the heater and absorber modules in either a leading edge configuration (Figure 17) or a flat array configuration (Figure 18). This support structure is sized to fit inside the 10-ft diameter altitude chamber located in the Radiant Heat Test Facility (Building 260) at NASA Johnson Space Center (JSC). When the support structure is configured for the flat configuration, up to twenty-four heaters can be arranged side by side to form a flat, horizontal heating array. When the support is configured to test wing leading edge sections, heaters and absorbers are attached to contoured mounting plates. The mounting plates provided with the array are fitted to a particular leading edge section. Other contoured surfaces can be tested by replacing these mounting plates with ones designed to support the heaters and absorbers around the desired contour.

The base of the support structure is formed by parallel 4-inch coolant headers with appropriate cross member stiffeners between them, and support pads along the outer edges. Two short nozzles with bolted flanges are located atop each header opposite each other. One nozzle on each header is deadheaded and acts as a support point only. The other two, located diagonally from each other are connected to the header coolant passages. When configured to test leading edge test articles, two U-shaped coolant manifolds fabricated from 4-inch pipe and weld fittings are bolted in place on top of the header nozzles. The inner surfaces of the support structure's water manifolds are electroless nickel plated for corrosion protection and the



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PYROMETER CALIBRATION DATA SUMMARY

Equation form:

$$T = \left(\frac{B}{C - \ln \left[\frac{V_o}{\epsilon} \right]} \right) - 460$$

where: T = Temperature, °F

V_o = Pyrometer output, millivolts

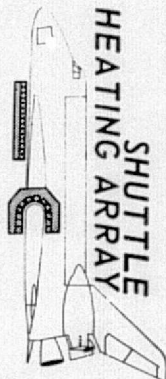
ε = Surface emissivity

B, C = Constants

with values of B and C as follows:

Pyro S/N	B	C
345	2.9403x10 ⁴	10.6841
369	2.8763	10.9737
370	2.9132	10.6321
371	2.9107	10.9080
372	2.9099	11.0440
373	2.8968	11.0415
374	2.9617	11.3542
375	2.8456	10.9489
376	2.9028	10.9971
377	2.9042	10.7079
378	2.8740x10 ⁴	10.6831

Pyro S/N	B	C
379	2.9135x10 ⁴	10.9066
380	2.9300	11.0587
381	2.8907	10.8506
382	2.8991	10.9191
383	2.9279	11.0121
384	2.9273	10.7947
385	2.8783	10.9392
386	2.8922	10.6329
387	2.9224	11.0190
388	2.9468	10.8614
389	2.9319x10 ⁴	10.9548



SHUTTLE
HEATING ARRAY

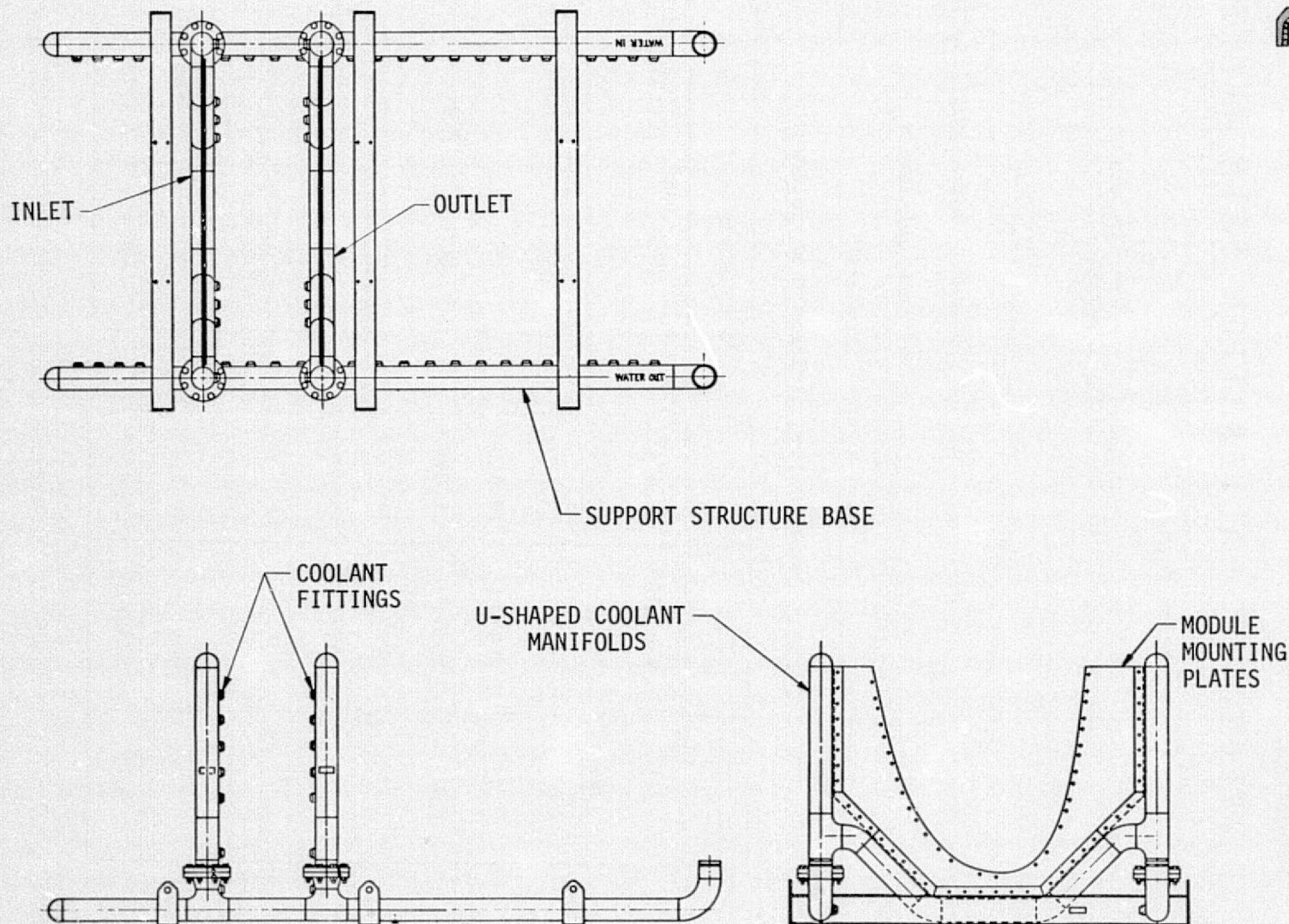
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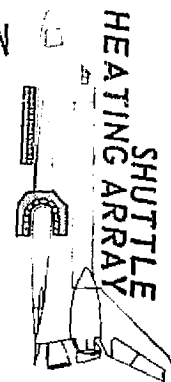
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HEATING ARRAY SUPPORT STRUCTURE LEADING EDGE CONFIGURATION



HEATING ARRAY SUPPORT STRUCTURE - FLAT CONFIGURATION

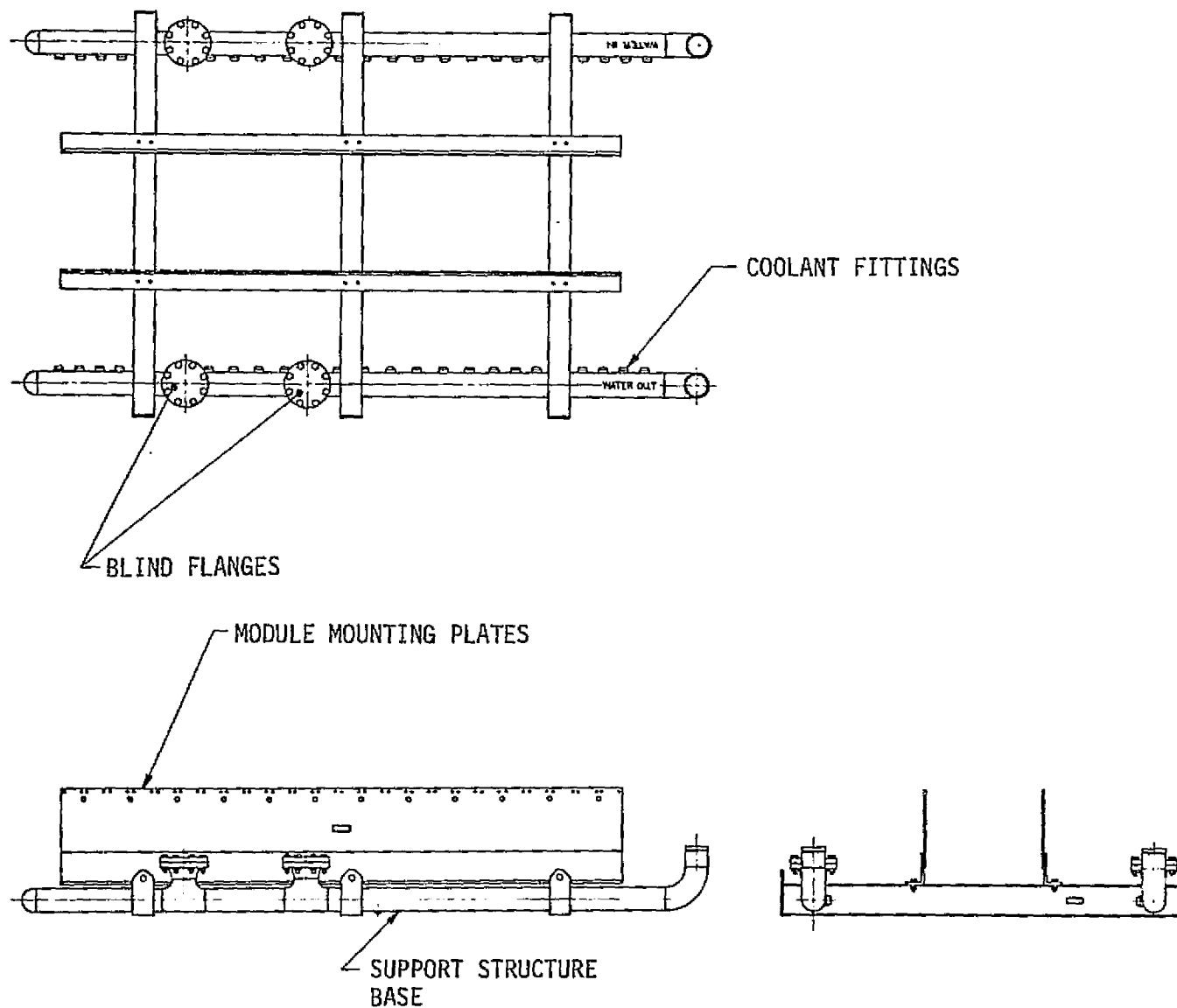


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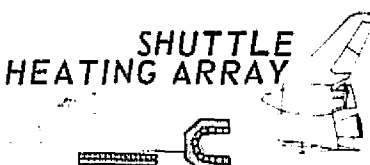
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exterior surfaces of the support structure are painted with solvent resistant polyurethane paint. Welded to the inside of these U-shaped manifolds are attachment flanges to which module mounting plates are bolted. The array is formed by bolting the individual modules to these plates around the contour of a leading edge shaped cutout. Fittings for individual coolant supply and return hoses to each module are spaced around the periphery of the manifolds. The coolant path thus formed is through one 4-inch header, to a U-shaped manifold, through the heater and absorber modules connected in parallel, to the other U-shaped manifold and header, to the coolant system return. The assembled leading edge heating array is shown in Figure 19. Eight 72 inch heater modules and seven 72 inch absorber modules are bolted to support plates to form the test envelope for a Shuttle leading edge test article.

When the support is configured to support heaters in a flat array, the U-shaped manifolds are removed and the open flanged nozzles are capped with blind flanges. Module mounting plates are then bolted to the cross member stiffeners of the support structure base. The flat array is formed by bolting the individual modules to these plates. Figure 20 shows two flat array configurations assembled on the support structure, twelve 72 inch heater modules and ten 48 inch heater modules. Fittings for the individual coolant supply and return hoses to each module are located along the inside of the base 4-inch coolant headers (See Figure 21). The coolant path thus formed then is through one 4-inch header, directly to the heaters, to the other 4-inch header, and then to the coolant return.

3.5 PERFORMANCE CHARACTERISTICS - The heater module performance characteristics will meet or exceed all the following specifications:

Maximum Temperature - Capable of sustaining 3200°F on the surface of a test article with thermal characteristics similar to Shuttle wing leading edge.

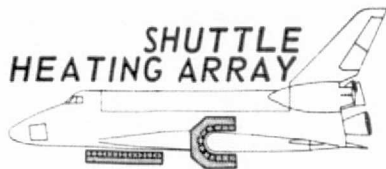
Spanwise Uniformity - Capable of providing a minimum heat flux along a 60 inch span of not less than 85% of the maximum heat flux during steady state operation at peak temperatures (72 inch configuration only).

Heating Rate - 600°F per minute between 80° and 2800°F.

Operating Pressure Range - 0.5 to 760 torr inert atmosphere.

Power Control - Heater is designed to operate off of standard ignitron power controllers through a 4:1 stepdown transformer.

Voltage & Current - To nominally operate at 3200°F, 65 volts are applied which results in a current of approximately 1400 amps.



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ASSEMBLED LEADING EDGE HEATING ARRAY

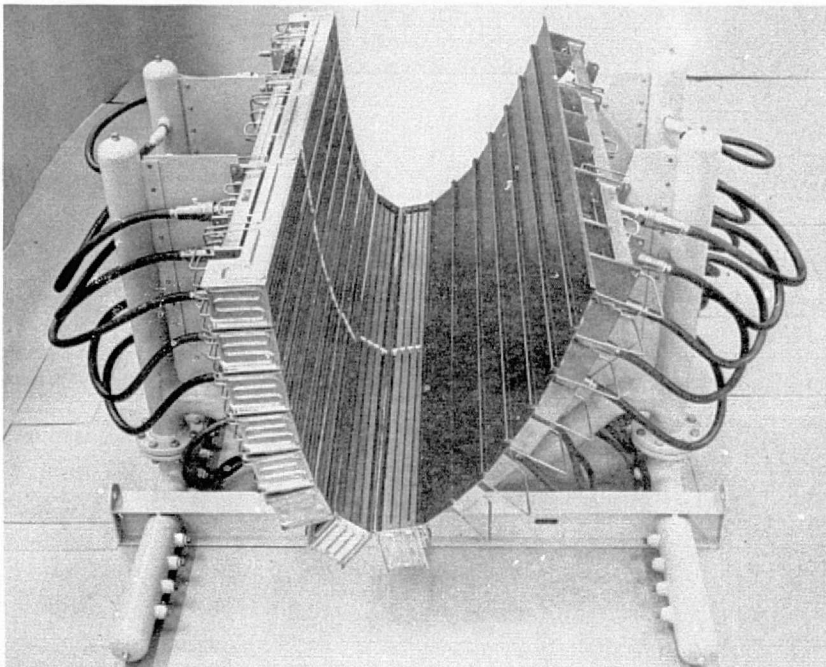
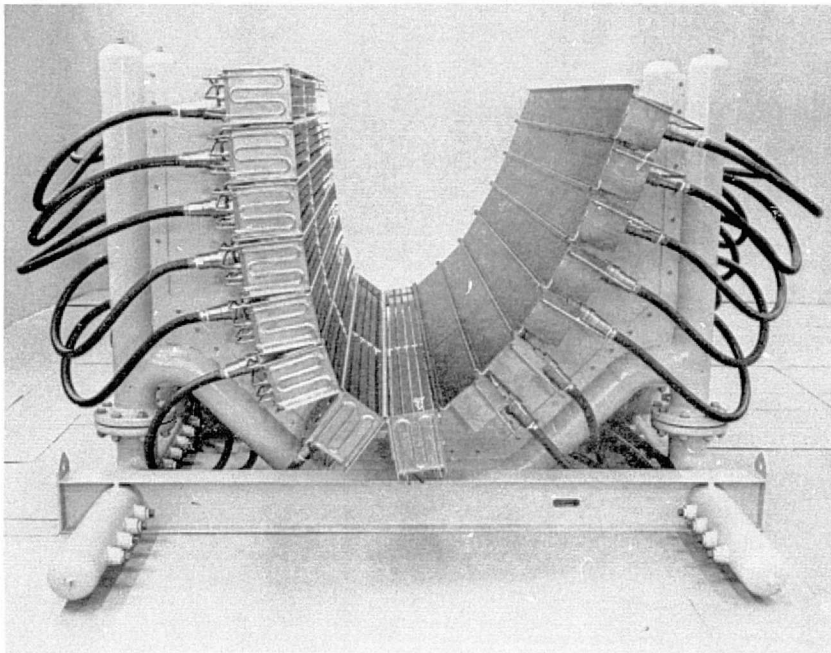
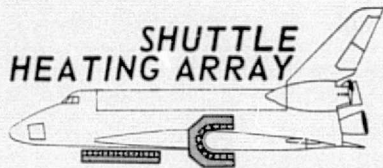


FIGURE 19



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ASSEMBLED FLAT SURFACE HEATING ARRAY

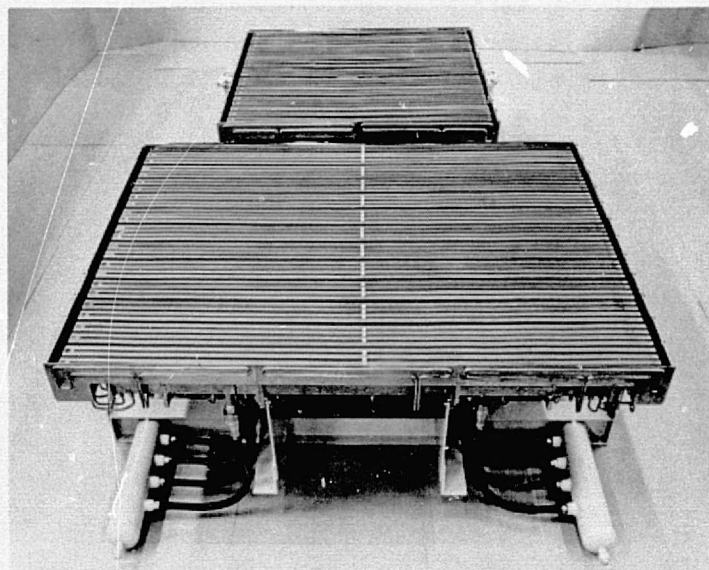
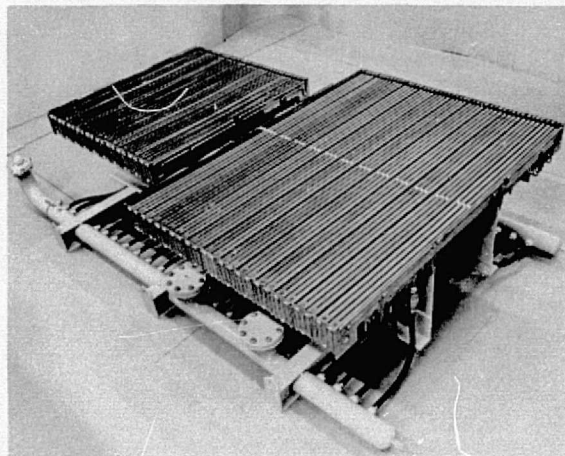
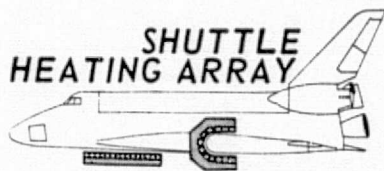


FIGURE 20



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VIEW OF THE ASSEMBLED FLAT SURFACE HEATING ARRAY SHOWING COOLANT HOSE CONNECTIONS

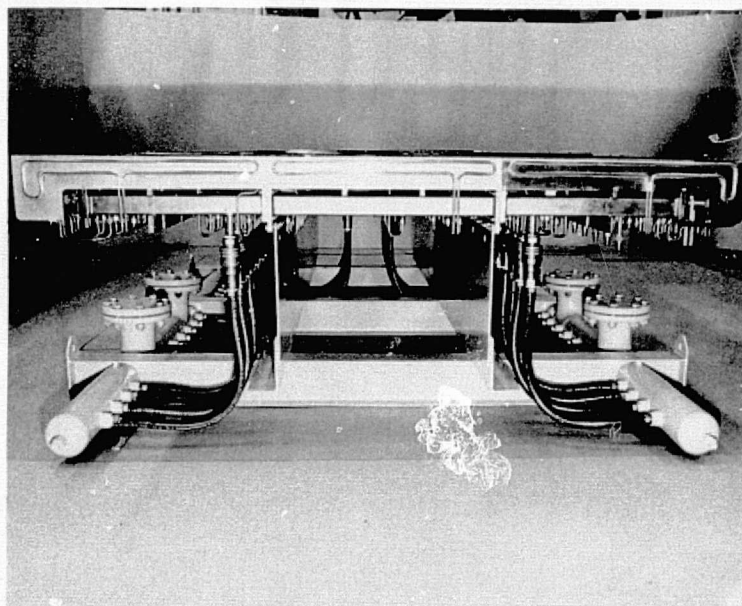
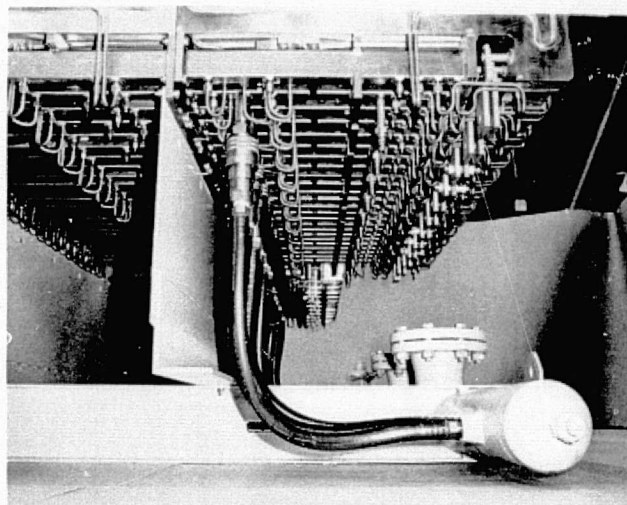
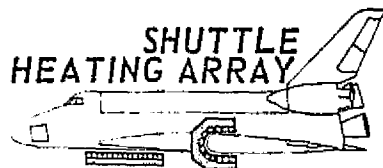


FIGURE 21



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4.0 FINAL DESIGN

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4.0 FINAL DESIGN

The final design of the Leading Edge and Flat Surface Heating Array was the culmination of effort which involved definition of the design goals and the design approach, preliminary design and system analysis, component feasibility testing, and finally the detailed design drawings and specifications.

4.1 DESIGN APPROACH - The approach used to successfully design the Leading Edge and Flat Surface Heating Array, after initially defining the design goals, consisted of a systems analysis to determine the optimum configuration, followed by component level analysis and feasibility testing intended to enhance the credibility of the final design.

The major design goals for the heating array are summarized as follows:

Array Configuration - Such a size as to be able to test a wing leading edge of at least 60 inch span with adjustment provided to allow the leading edge radius to vary from 3.4 to 6 inches. The array shall be capable of being expanded to test larger hardware.

Spanwise Uniformity - A minimum incident heat flux along the span of a heating zone shall not be less than 85% of the maximum incident heat flux during maximum steady state operation.

Maximum Temperature - 3200°F on the surface of test specimen which shall be maintained for 10 minutes.

Minimum Temperature - Initiation of heating when test article is at -250°F.

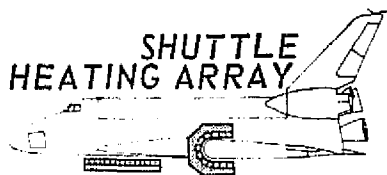
Heating Rate - 600°F per minute between 80°F and 2800°F.

Cooling Rate - 80°F per minute between 2800°F and 1500°F.

Cordwise Temperature Distribution - Shown in Figure 22.

Pressure Range - 0.5 to 760 torr inert atmosphere (nitrogen).

The array was designed to have sufficient waste heat removal capacity to prevent heat dissipation to the uncooled vacuum chamber walls with coolant flow rates and temperatures that are compatible with the JSC closed-loop cooling system. Further, the array was designed to use and be compatible with ignitron controllers furnished by JSC. Our approach to meeting the design and performance criteria was to use graphite heater modules, each a complete self-contained unit mounted to an array support structure in such a way that the number, position, and angular orientation of modules in the array may be easily varied to suit the specimen to be tested. Analytical studies of the array performance determined the dimensions, spacing, and maximum power dissipation required of each module in the array.



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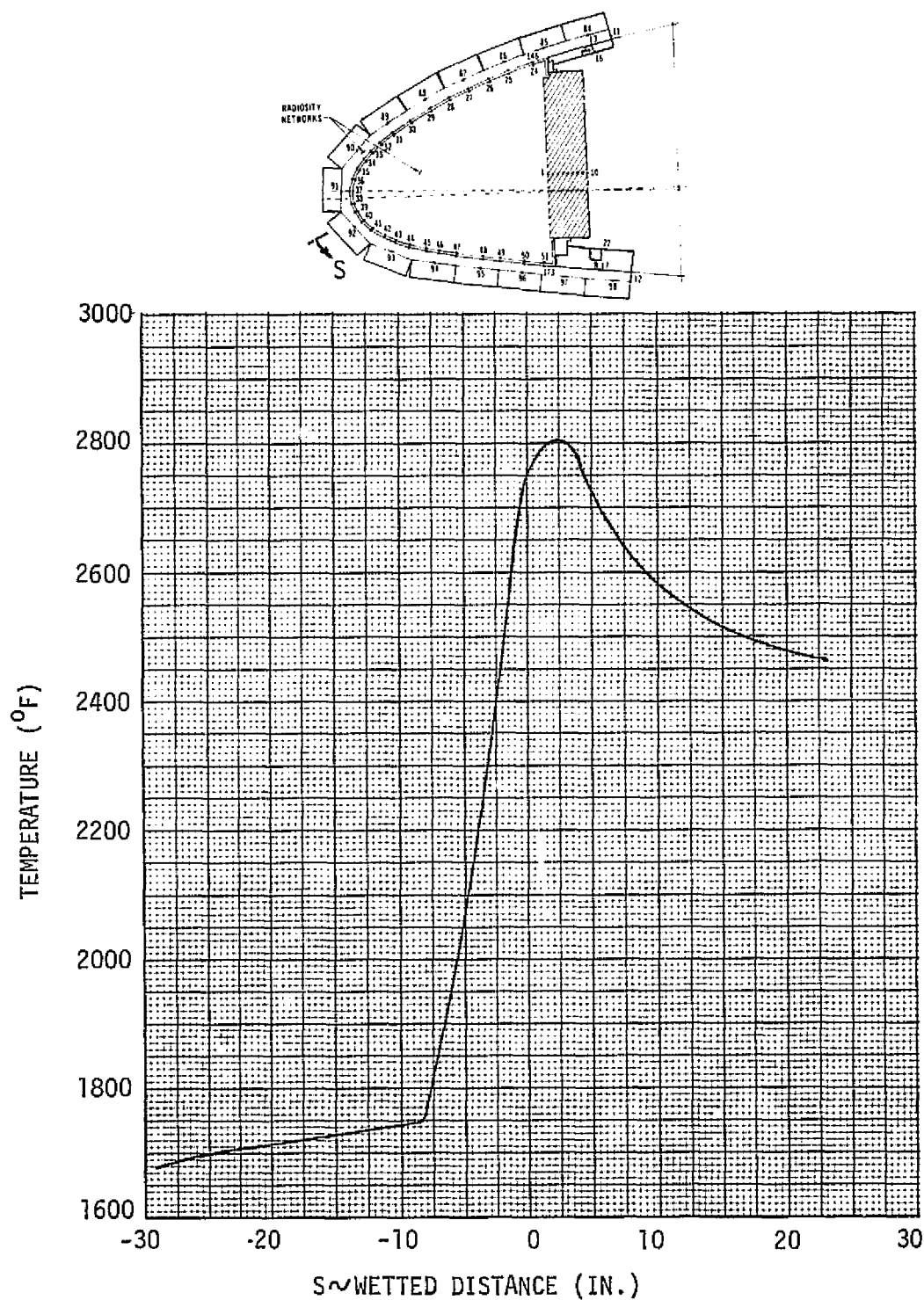
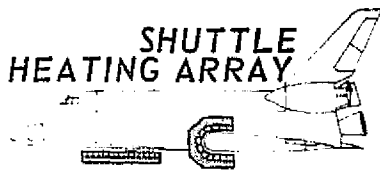
DESIRED LEADING EDGE TEMPERATURE DISTRIBUTION
(67% SEMISPAN)

FIGURE 22

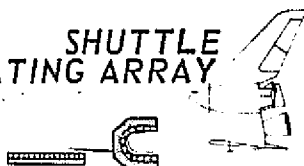


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A configuration study was performed including both the 60 inch leading edge heater and the flat surface array. The studies were pointed at maximum heater flexibility to provide for future expansion, possible heater interchangeability, and maximum parts commonality. This enabled a recommendation to be made during the course of the program as to the type of heater which would provide the maximum cost effectiveness.

Phase I analysis and testing indicated that gold-plated reflectors are potentially more efficient than reflectors coated with other materials. In line with this, we performed fabrication technique trade studies along with potential vendor selection and in-service evaluation of gold-plated reflectors. Also, analytical studies were performed to determine the transient thermal response of the heater array specimen configuration for both the heating and cool-down cases. These studies included investigation of both the individual module and the entire array with verification of the results being obtained through testing of a 36-inch prototype heater. Further, the 36-inch prototype heater, updated to incorporate all design modifications, was used to test such performance parameters as maximum temperature, arcing and corona affects, and heating uniformity. The performance testing apparatus was left intact throughout the design effort for purposes of verifying analyses and evaluation of design concepts. A study of methods of measuring specimen surface temperatures was conducted with the intent of designing a temperature measurement system capable of being used for both data acquisition and control purposes. A prototype of this system was constructed and tested with the 36-inch prototype heater and a representative test specimen to demonstrate the suitability of the proposed design. After the decision was made on the most suitable heater configuration, the effort culminated in a final detailed design of the entire heating array. The final design package consists of drawings, specifications, standards, and other information necessary to fabricate the leading edge heating array, incorporating all recommendations and advances gained from the foregoing effort.

4.2 FLAT SURFACE HEATING ARRAY DESIGN - The design of the flat surface heating array was based on using the basic heater module used in the leading edge heating array and adapting the support structure for a flat configuration. An array with a heated area of 48 x 96 inches can be assembled using the eight leading edge heater modules in the 48-inch configuration with fourteen additional 48-inch modules.



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Additionally, the array was to have the ability to test a flat surface article, 48 inches by 60 inches, with a design capability of maintaining a minimum heat flux uniformity of 85 percent. This is accomplished using twelve 72-inch heater modules.

The final design, which was approved by the Contract Technical Monitor prior to fabrication consisted of: the drawings, specifications and standards necessary to fabricate the flat surface heating array.

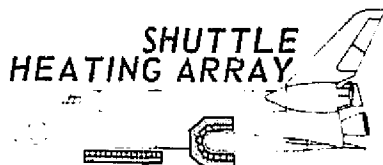
Sufficient flat surface heater modules, consisting of the eight 72-inch leading edge modules along with four additional 72-inch modules and ten 48-inch modules, are provided to satisfy the array requirements. These modules are identical in design to the leading edge modules in order to achieve maximum flexibility and interchangeability. Side reflectors are not required on heater modules designated for the flat heater array, but provision is made for mounting such reflectors. Each module is equipped with a pyrometer.

A support structure capable of supporting all heater modules was designed. This structure has the capability to accommodate flat or moderately curved test configurations and can be readily adjusted for other test article configurations. In addition it accommodates heaters in both the extended (72-inch length) or collapsed (48-inch) configuration. The support structure has sufficient flexibility to allow testing with any number of heaters up to a full complement of 24. The evolved design is described in detail in preceeding sections of this report.

4.3 INTERFACE REQUIREMENTS - MDC has performed interface requirement investigations sufficient to demonstrate that the end product(s) resulting from this procurement fully meet the NASA-JSC intended usage. Documentation delivered with end product hardware includes technical description and/or sketches (where applicable) of all interfaces in sufficient technical detail to permit incorporation of the end product hardware into systems or subsystems as applicable without the need of further contractor effort.

The coolant interfaces with the JSC closed loop coolant system occur at the end of the support structure base headers. Valves, pipe sections, and couplings are provided to connect the heating array to the coolant supply and return penetrations in the altitude chamber.

The electrical power interface between JSC provided equipment and the heater occurs at the bus plates of each heater module. Provision is made to connect a two-conductor water-cooled wire to the bus plates of each heater module. If power



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cables other than the type provided for is used, some adaptation may be necessary to interface with the type power cables utilized.

Instrumentation interface is provided at a barrier terminal strip attached to the main coolant headers of each heater and absorber module. The leads from the pyrometer assemblies and the coolant flow switches are routed to this terminal strip, where JSC instrumentation wire bundles can be easily connected.

4.4 DESIGN CALCULATIONS - Extensive analyses were performed in conjunction with the design and preliminary testing of both the heating array and the individual heaters. This paragraph summarizes, in some detail, the most pertinent of those calculations.

4.4.1 Thermal Analysis of Entire Array - Thermal analyses were performed on typical leading edge test articles surrounded by heating arrays. As an example, the analysis performed for the test article at 67% semispan on the Shuttle leading edge is discussed in detail. Steady state heat transfer analysis was performed to predict performance of the heating array surrounding this leading edge. These analyses were performed using a thermal model (Figure 23) implemented on MDC's HEATRAN general thermal analyzer computer program, which considered heat conduction and radiation between various components of the test setup. Automated view factor calculations were used in a radiosity network solution for handling radiant energy exchange, including reflections. This model was employed to size the width of the modules, the spacing between the modules and specimen surface, and the arrangement of the modules around the specimen. The inverse solution technique was performed to determine power and heater element temperature. This consisted of specifying temperatures representing a typical Shuttle flight temperature distribution at peak heating conditions at various points around the leading edge and solving for the individual heater module temperature and the power required to maintain that temperature including that waste heat absorbed by the heater modules. The calculated and desired leading edge temperature distributions are compared in Figure 24. The solid symbols are the control nodes for the heater modules and were specified in the thermal analysis. The open symbols represent calculated temperatures from the thermal model. The predicted heating element temperatures and input powers (or heat flux) required to provide these temperatures are presented in Figure 25. The power shown for each module is on a unit area basis of 1 square foot. The negative powers indicate where energy absorbers are required. These analyses along with companion analyses indicated that the heating array would produce the environment required to test Shuttle leading edge sections.



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COMPUTER MODEL OF HEATING ARRAY AND SPACE SHUTTLE LEADING EDGE

(67 PERCENT SEMISPAN)

- NODES 1 THRU 10 AND 13 THRU 22 ARE HRSI
- NODES 11 AND 12 ARE FIBROUS INSULATION GUARDS
- NODES 23 THRU 52 AND 146 THRU 173 ARE CARBON/CARBON
- NODES 84 THRU 98 ARE MODULES

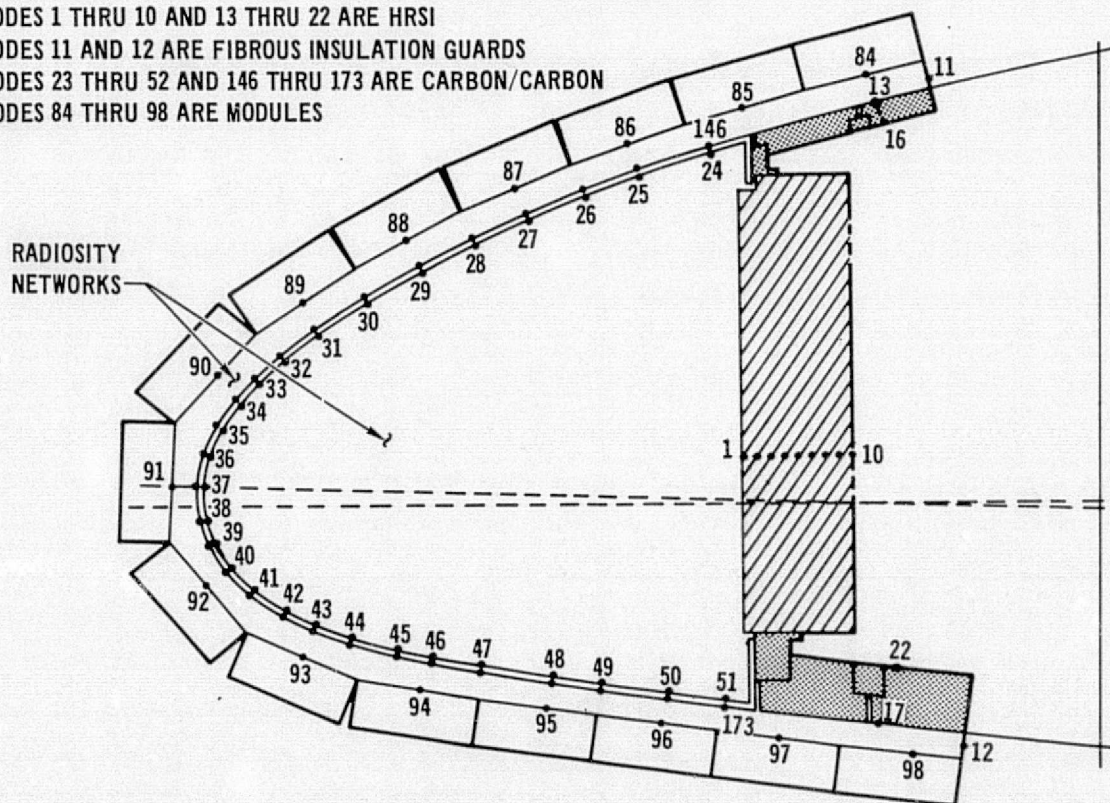


FIGURE 23

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LEADING EDGE TEMPERATURES PRODUCED BY THE EIGHT HEATER MODULE/SEVEN ABSORBER CONFIGURATION

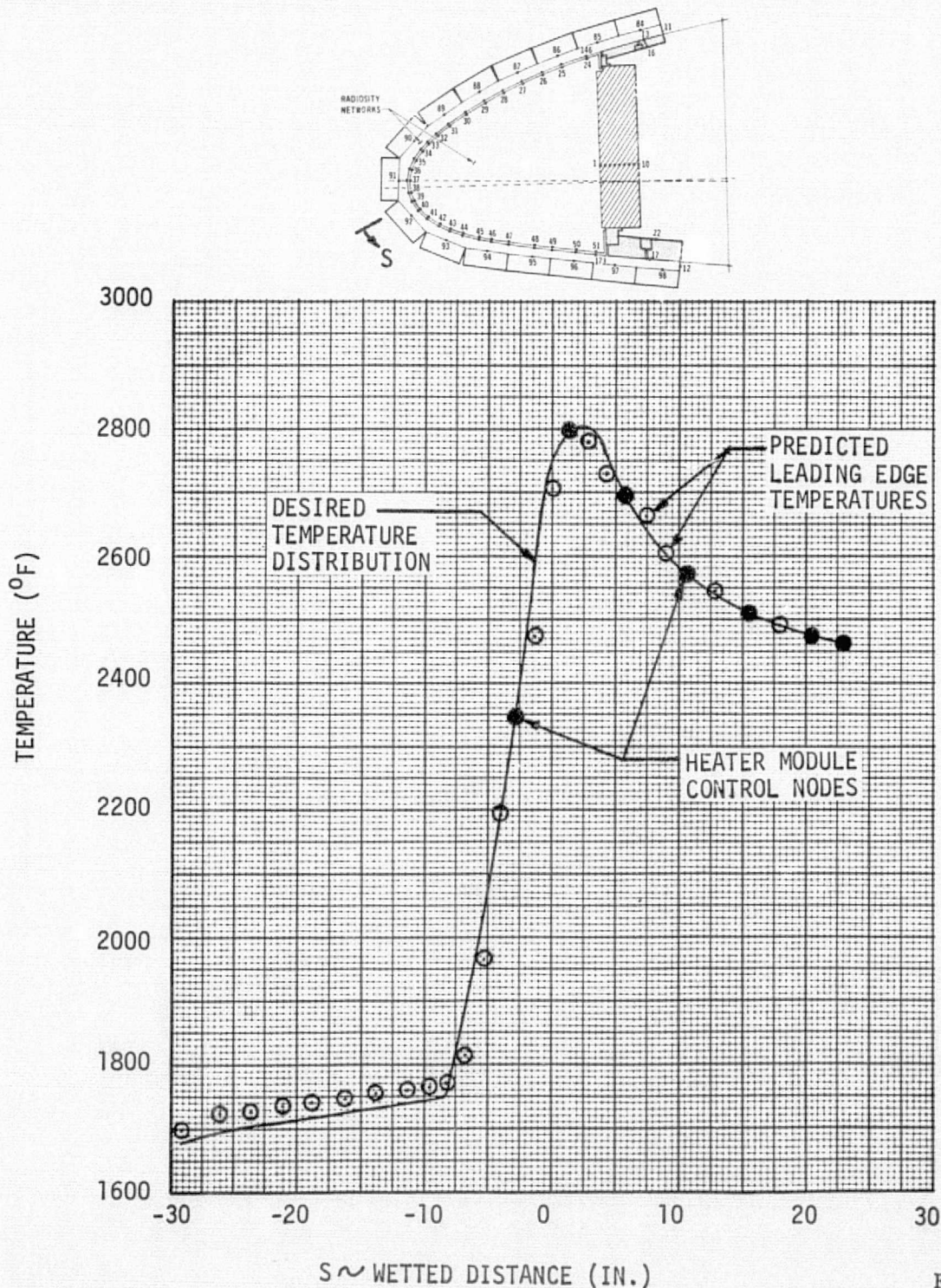
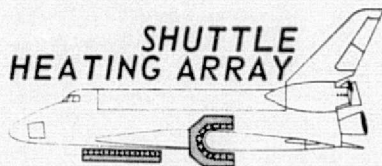


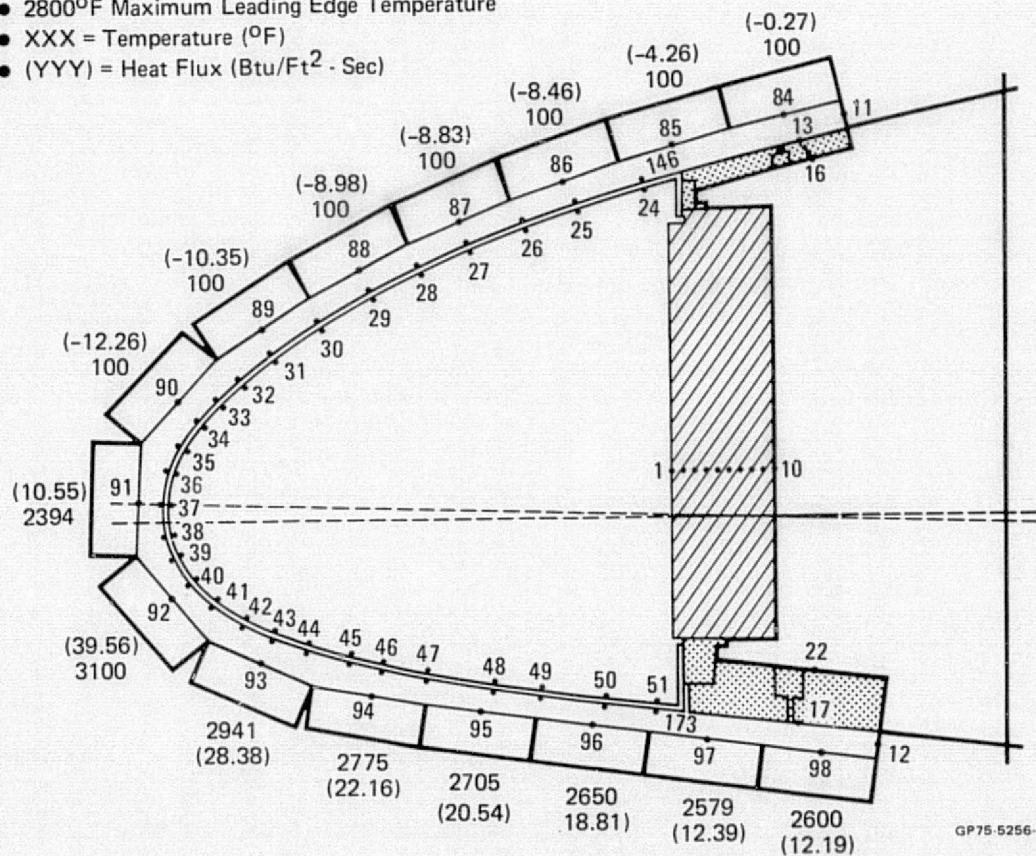
FIGURE 24



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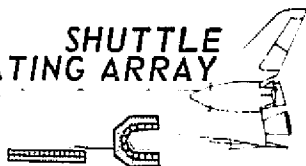
PREDICTED HEATING ARRAY TEMPERATURE AND POWER REQUIREMENTS FOR THE EIGHT HEATER MODULE/SEVEN ABSORBER CONFIGURATION

- Steady State Analysis
- 2800°F Maximum Leading Edge Temperature
- XXX = Temperature (°F)
- (YYY) = Heat Flux (Btu/Ft² - Sec)



GP75-5256-7

FIGURE 25



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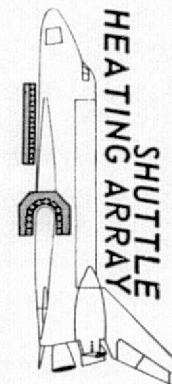
4.4.2 Thermal Analysis of Heater Module - Heat transfer analysis were performed for both the prototype heater module (36 inch long) and the 72 inch heater module. The predicted performance for each module was compared with experimental data obtained on fabricated hardware. Both units contained serpentine graphite heater elements, gold-plated reflector panels, self-holding tapered heating element supports and a lever system to prevent excessive element sag and compensate for thermal expansion of the element during heater operations. Gold-plated reflectors were used to increase heater operating efficiency and enhance the heat flux uniformity to the test articles. The prototype heater module was used to conduct performance tests to determine the effective reflectance of the gold-plated reflectors, map the incident heat flux uniformity provided to the test article, and substantiate detailed thermal predictions.

A test article simulating a section of the wing leading edge was constructed for each heater module. The test articles and heater module were instrumented to measure incident heat flux on the specimen surface, energy absorbed by the heater module, power input to the heater module, and the test article surface and heater element temperatures.

An 83 node thermal model (Figure 26) was implemented on HEATRAN to calculate heater module heat transfer characteristics and performance. This model considered heat generation in each of 19 heater nodes, 3-dimensional radiant heat transfer and a 38 node radiosity network between heater elements, test article and reflectors, as well as thermal conduction within the heater elements and cooled supports. The thermal model was set up so that only a few hallmark dimensions needed to be changed to evaluate a different length heater module. Heat generation within each heater node is included in the model. Figure 27a shows the electrode end of the 72 inch heater module with the graphite element attached to the water cooled copper pin. The elements are .42 inches thick with .75 inch thick end blocks. The bottom reflector extends to within .25 inch of the electrode pin. The test specimen is shown positioned .25 inch above the side and end reflectors. Figure 27b shows the expansion end of the heater module. The thermal model does not reflect the design change made to the expansion lever during testing.

4.4.2.1 Effective Reflectance of Gold Reflectors - Values of effective reflectance for the reflectors were developed using measurements of test specimen and heater element temperatures while operating at various steady state power levels.

THERMAL MODEL OF HEATER MODULE

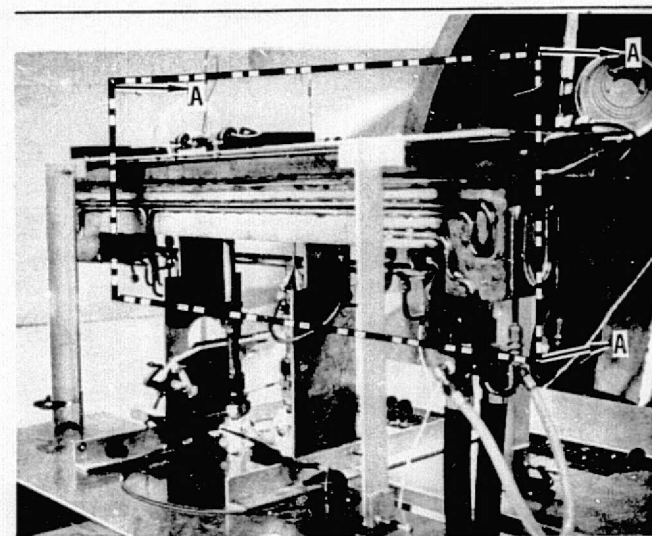


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- HEAT GENERATED PER UNIT VOLUME OF GRAPHITE
- 3-D RADIATION HEAT TRANSFER
- CONDUCTION
- CALCULATES TEMPERATURE DISTRIBUTIONS IN SPAN-WISE DIRECTION
- CIRCLED NUMBERS ARE RADIOSITY NODES
- CONNECTIONS TO RADIOSITY NODES ARE REPRESENTED BY / SYMBOL

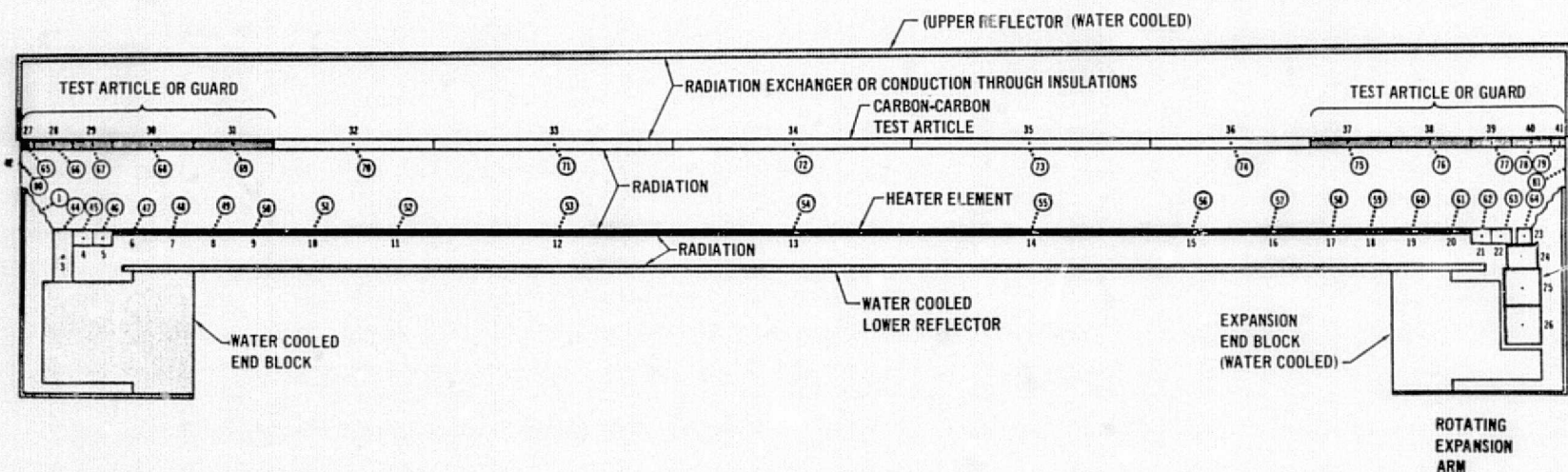
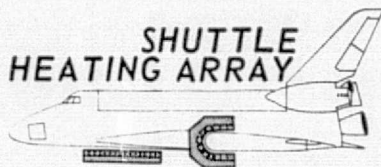


FIGURE 26



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THERMAL MODEL OF 72 INCH HEATER MODULE,
ELECTRODE-END

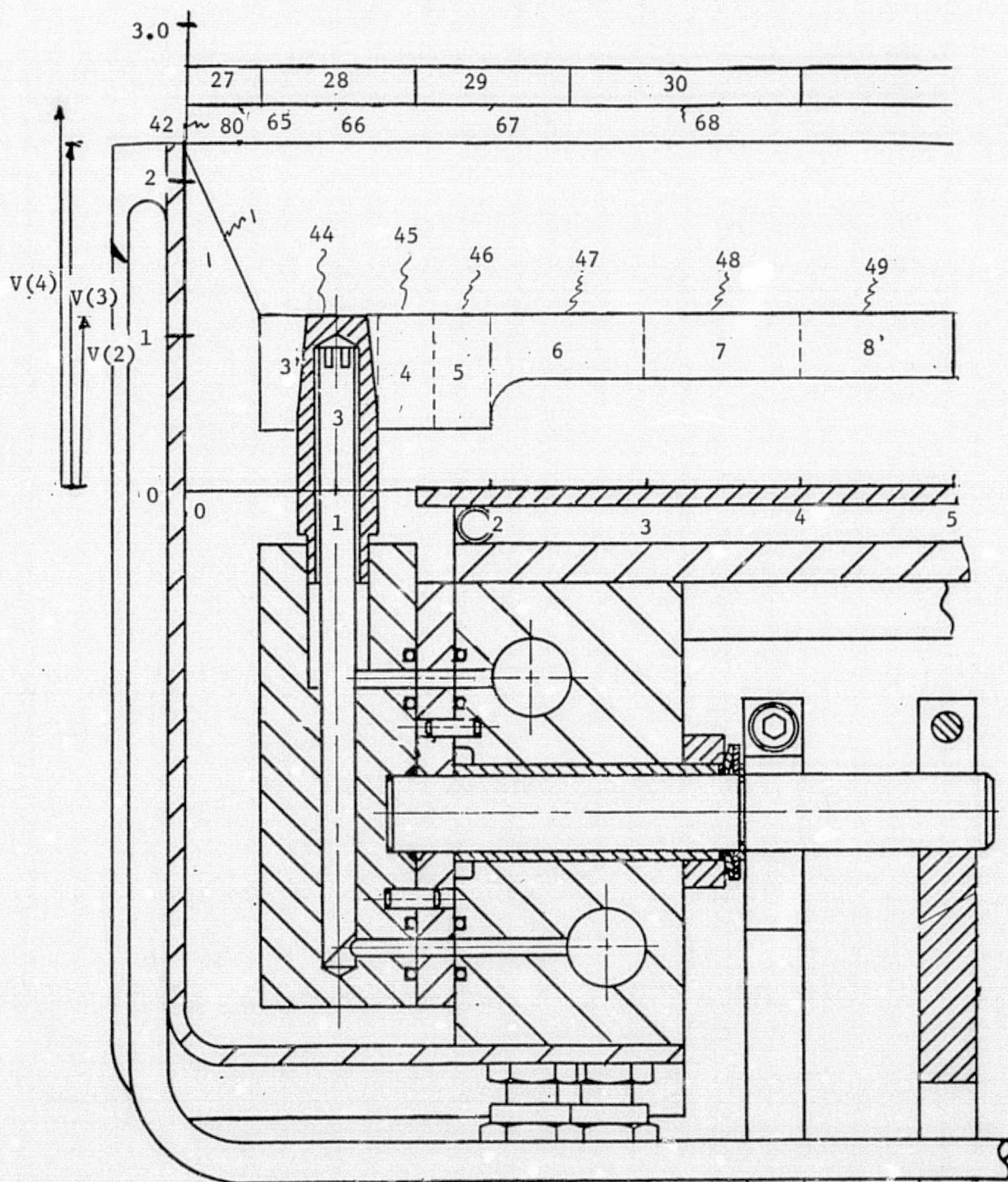


FIGURE 27a



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THERMAL MODEL OF 72 INCH HEATER MODULE,
EXPANSION-END

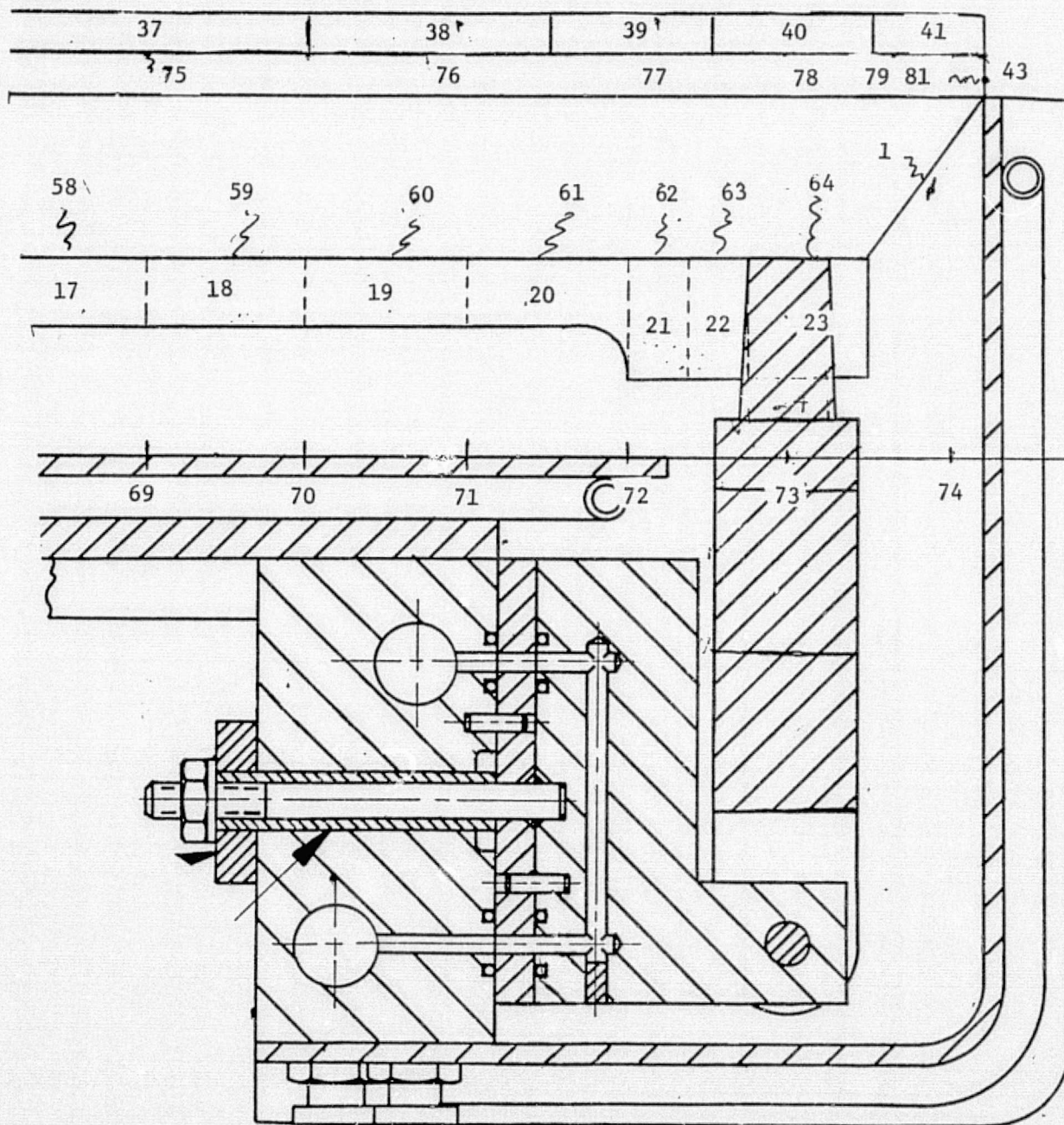
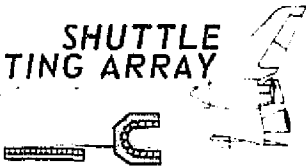


FIGURE 27b

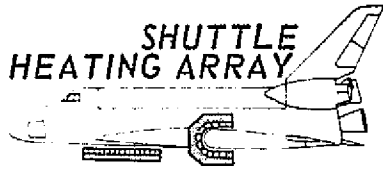
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These data were then compared to analytical predictions based on various assumed values for reflectance. Under actual operating conditions, outgassing products from the test article deposit to some extent on the gold reflectors. The effective reflectance was measured with clean reflectors and after a period of operation. A comparison of measured and predicted test specimen temperatures is shown in Figure 28. The measured data taken with clean reflectors show an effective reflectance slightly greater than 0.80. Data taken after a period of operation indicates the effective reflectance decreases to 0.70. This is significantly higher than the effective reflectance of 0.55 for chrome-plated reflectors which was utilized in earlier heater designs. A similar comparison was made between measured and predicted heater element temperatures with the same results. Based on these tests, an effective reflectance of 0.80 describes the heater module performance when the reflectors are clean and 0.70 when deposits are allowed to accumulate on the reflector surfaces.

4.4.2.2 Prototype Module Heat Flux Uniformity - Incident heat flux distribution along the test specimen were measured during a series of prototype heater module tests. A thermal analysis was performed to predict the temperature and heat flux uniformity for the prototype heater module using an effective reflectance of 0.80. The calculated test specimen and heater element temperature uniformity is shown in Figure 29. The heater element temperature decreases significantly near the water cooled electrode pin. The element temperature also decreases near the graphite pin attachment, but less significantly than at the electrode end. This decrease in element temperature near the ends of the elements results in a lower incident heat flux to the test specimen in these areas and, thus, lower test specimen temperatures. The predicted test specimen temperature distribution show the temperature to be uniform in the center of the module with the characteristic lower temperatures near the ends of the specimen. The measured heat flux uniformity from the performance tests is compared with the predicted uniformity in Figure 30. Excellent agreement is seen to exist, especially in the area where the uniformity level is 80 percent and greater.

4.4.2.3 72 Inch Heater Module Predicted Performance - The maximum heater element and test specimen temperatures were calculated as a function of power supplied to the heater elements (see Figure 31). The analysis was performed using the 0.80 effective reflectance. The computed temperatures were obtained for steady state conditions and an adiabatic test specimen. Figure 32 presents the calculated



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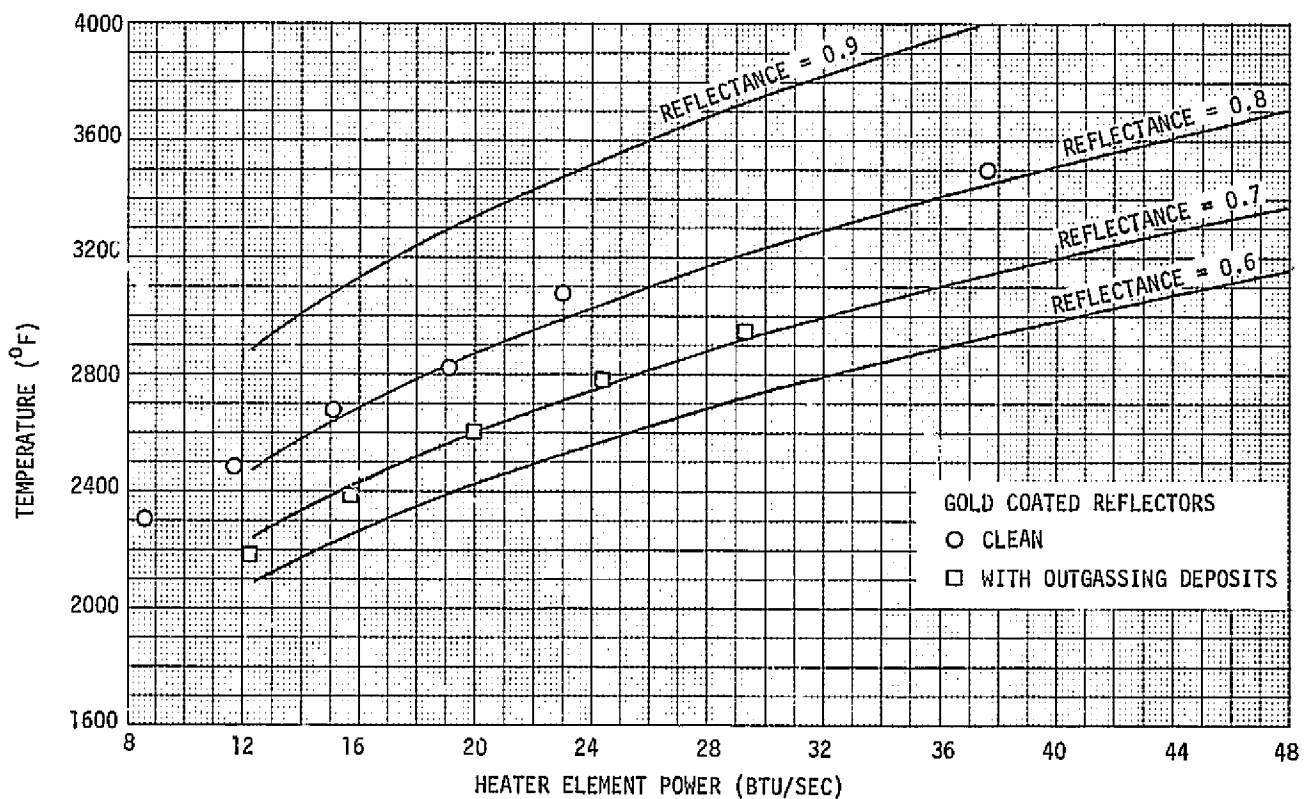
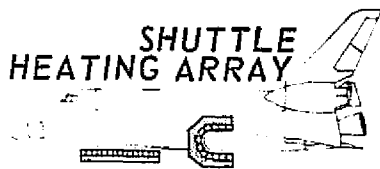
MEASURED AND PREDICTED TEST SPECIMEN TEMPERATURES
FOR THE 36 INCH PROTOTYPE HEATER MODULE

FIGURE 28



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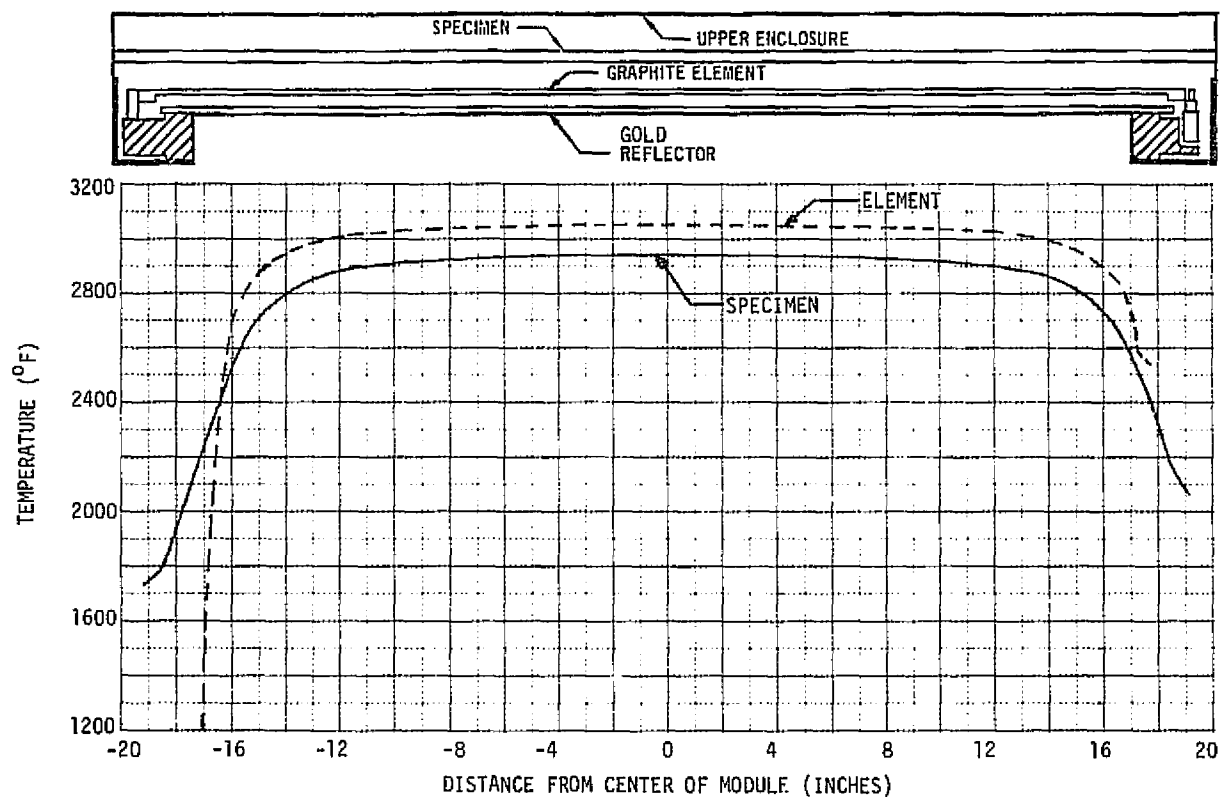
CALCULATED TEST SPECIMEN AND HEATER ELEMENT
TEMPERATURE UNIFORMITY FOR THE PROTOTYPE HEATER
MODULE

FIGURE 29



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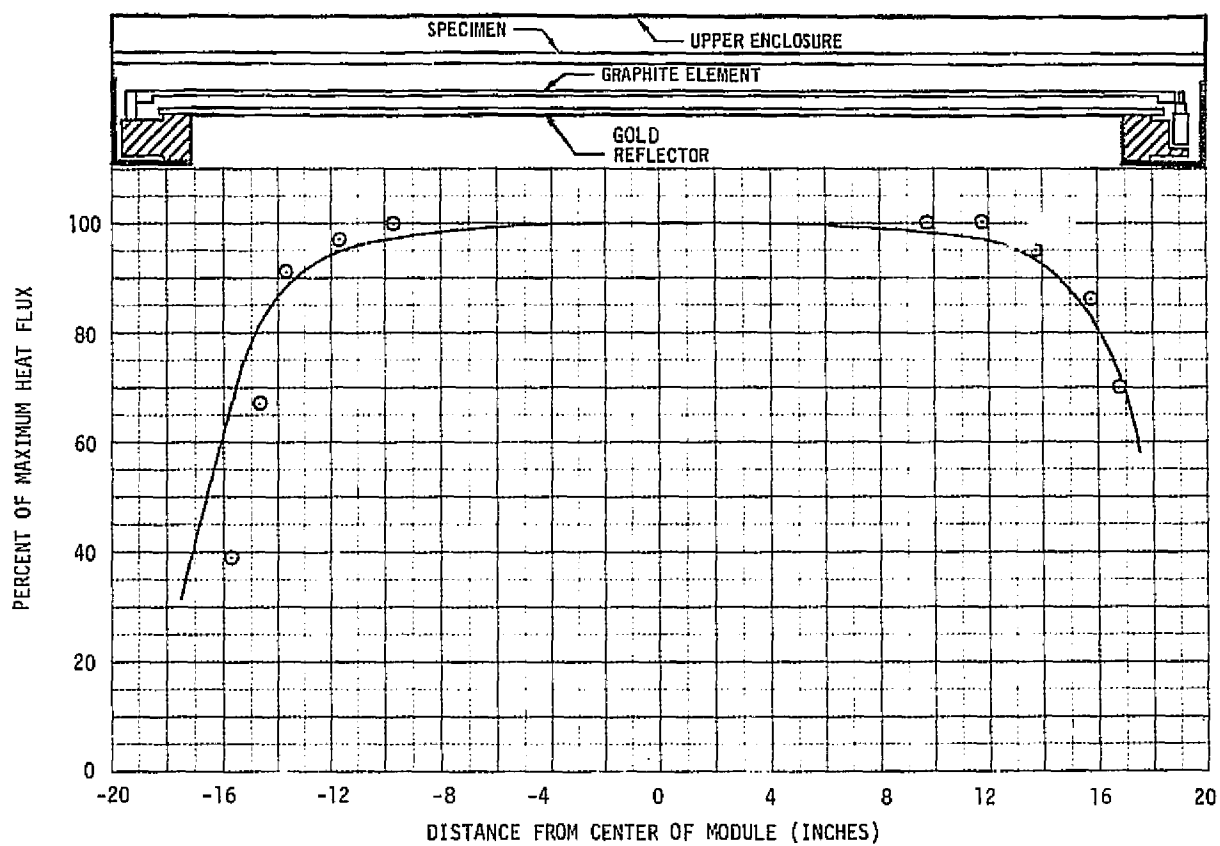
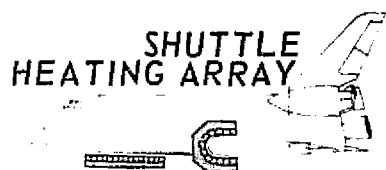
MEASURED AND PREDICTED HEAT FLUX UNIFORMITY FOR
THE 36 INCH PROTOTYPE HEATER MODULE

FIGURE 30



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CALCULATED PERFORMANCE CHARACTERISTICS
OF THE 72 INCH HEATER MODULE

- STEADY STATE ANALYSIS
- GOLD COATED REFLECTORS ($\rho = 0.80$)
- ADIABATIC TEST SPECIMEN

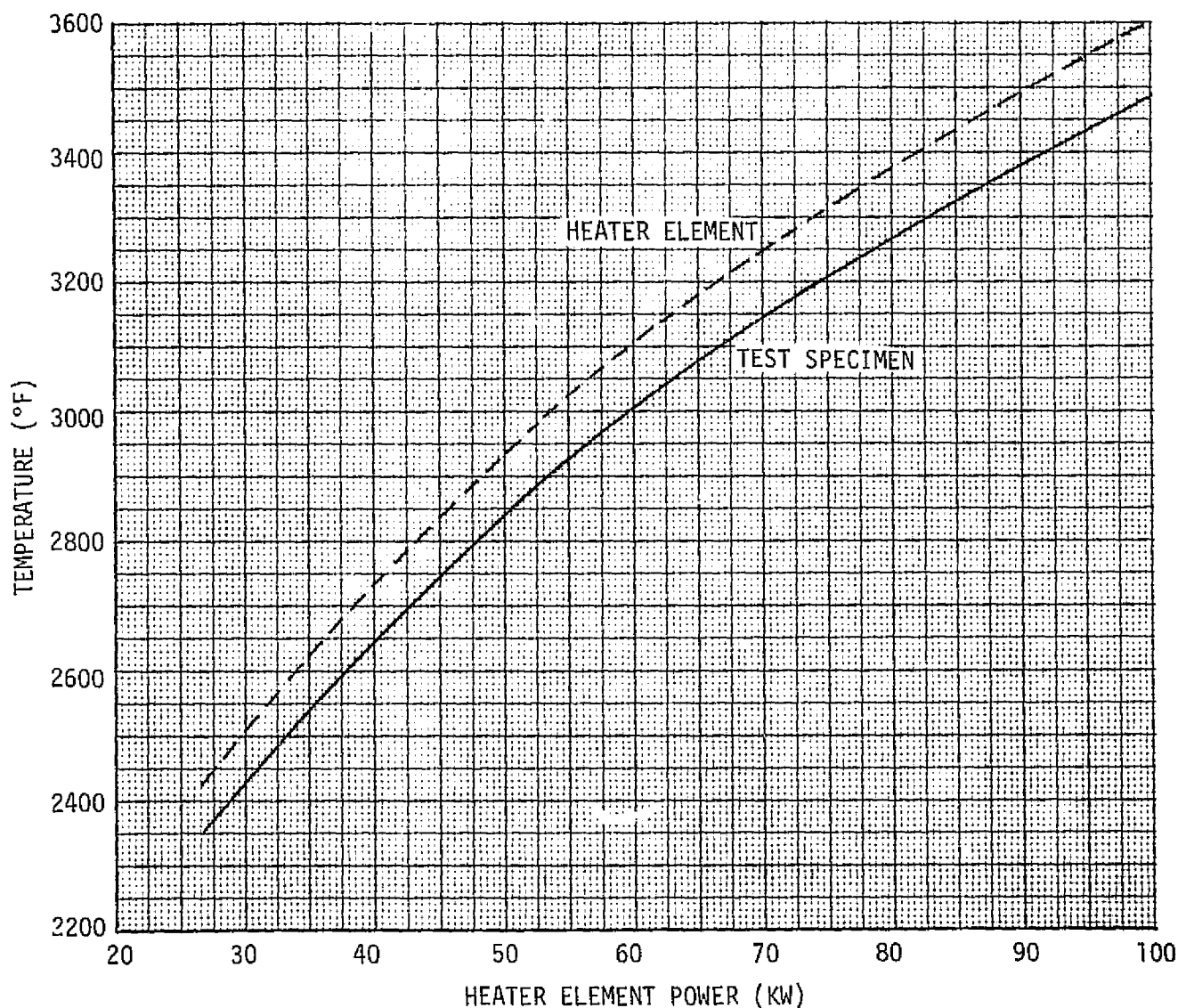
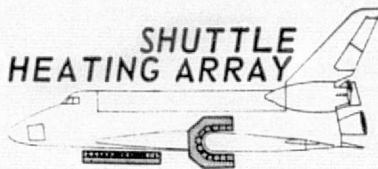


FIGURE 31



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.72 INCH HEATER MODULE CALCULATED TEST
SPECIMEN INCIDENT HEAT FLUX UNIFORMITY

- HEATER ELEMENT POWER = 53.1 KW
- STEADY STATE ANALYSIS
- GOLD COATED REFLECTORS ($\rho = 0.80$)
- ADIABATIC TEST SPECIMEN

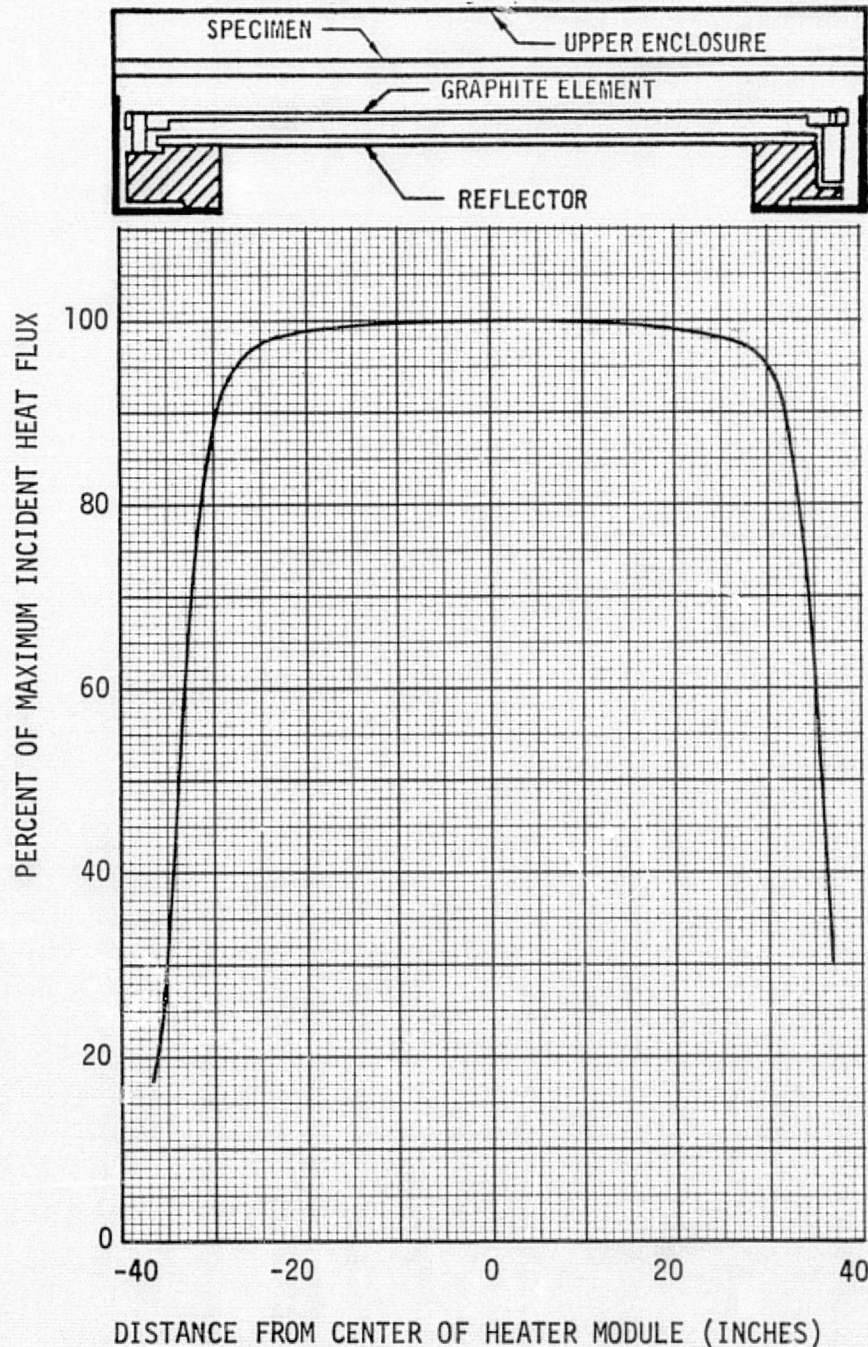
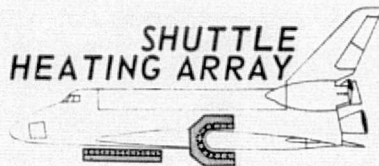


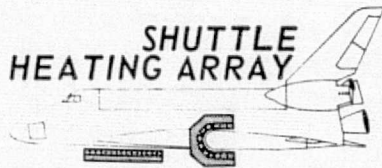
FIGURE 32

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incident heat flux distribution to the test specimen for 53.1 KW of heater element power. A 60 inch test article centered over the heater module is predicted to have a minimum uniformity of 88 percent. The calculated heater element and test specimen temperature distributions are shown in Figure 33. The low element temperatures at the electrode end is due to the elements being in direct contact with the water cooled electrode pin. The pin on the expansion-end is not actively cooled and therefore operates at much higher temperatures than the electrode pin.

4.4.2.4 72 Inch Heater Module Uniformity Test Results - The engineering model uniformity test consisted of 8 runs on a 72 inch heater module with an input potential of 60 volts and 60 KW being dissipated in the heater elements. During each run an incident heat flux uniformity measurement was made at a location on the test specimen. Figure 34 shows a summary of the data taken during these tests. The measurement location is expressed in inches from the center of the heater module. The measured uniformity is compared with the calculated uniformity in Figure 35. It can be seen that the measured uniformity is less than the calculated uniformity. However, the uniformity measurements indicate that 85% incident heat flux uniformity can be achieved for a 60 inch test article (-28.5 inches to 31.5 inches).

4.4.2.5 Refined Heat Transfer Analysis - The thermal model used to calculate the performance characteristics was refined to improve correspondence between the set of assumptions and actual conditions existing during performance testing. The test article used for performance testing was fabricated from graphite rather than carbon-carbon. Instrumentation indicated that the test article absorbed some of the heat supplied by the heater elements during the performance tests. The thermal model was changed to account for the heat transfer to the back of the test article. The inclusion of heat leak to the back of the test article resulted in an increase in effective reflectance of the gold reflectors from 0.80 to 0.83 in order to achieve the measured element and test article temperatures. The most significant improvement in the thermal model is a subroutine which calculates the heat generated in the element nodes as a function of element temperature. This subroutine accounts for the dependancy of the electrical resistivity property of 890S graphite with temperature. For a given element configuration and input voltage the individual electrical resistance for each node, the total resistance of the heater elements, the current, and the heat generated in the individual element nodes were computed. Figure 36 contains the electrical resistivity of 890S graphite as



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72 INCH HEATER MODULE CALCULATED TEMPERATURES

- HEATER ELEMENT POWER = 53.1 KW
- STEADY STATE ANALYSIS
- GOLD COATED REFLECTORS ($\rho = 0.80$)
- ADIABATIC TEST SPECIMEN

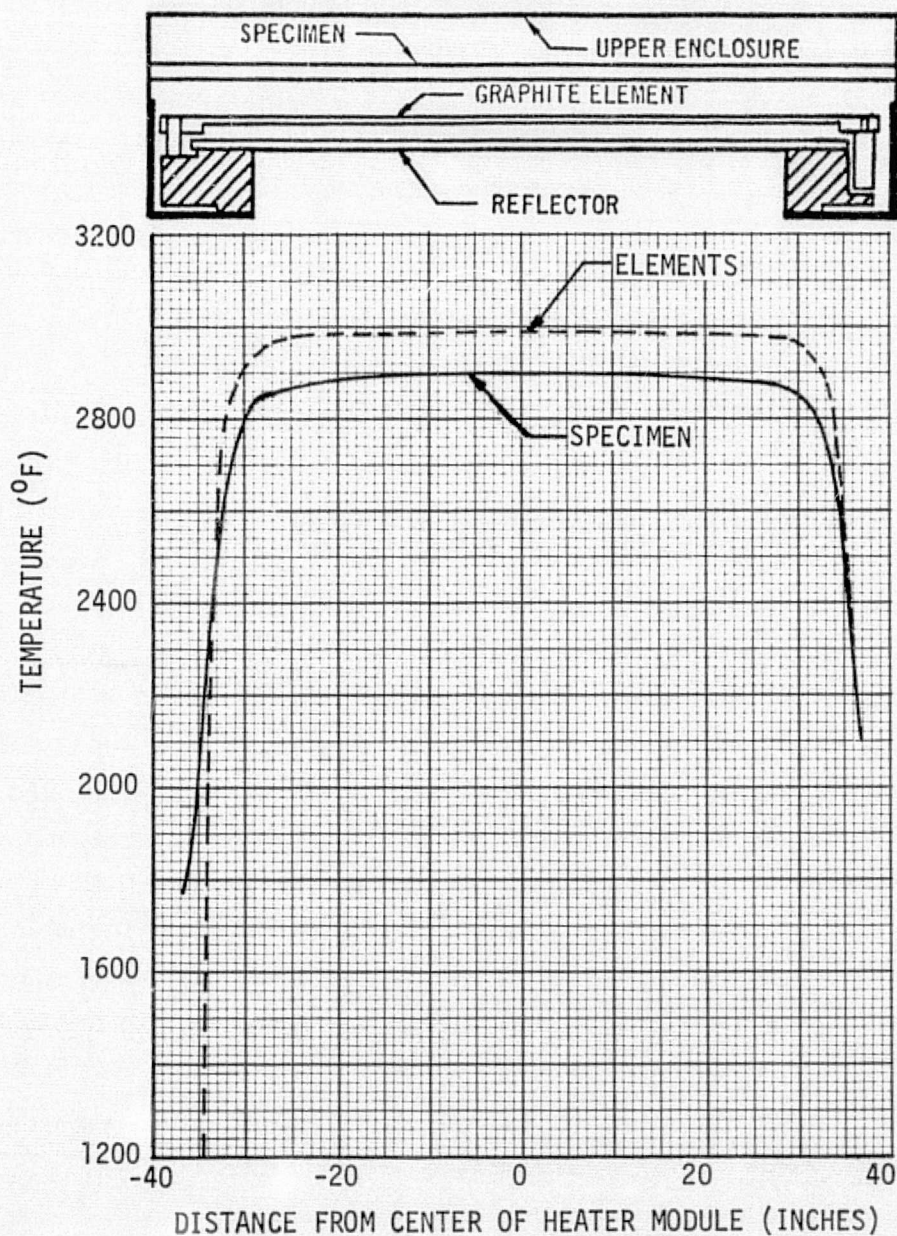
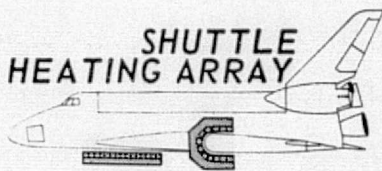


FIGURE 33



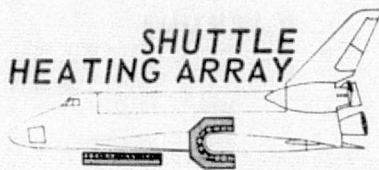
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ENGINEERING MODEL UNIFORMITY TEST RESULTS

RUN	V (VOLTS)	I (AMPS)	POWER (KW)	ELEMENT TEMP. (°F)		SPECIMEN TEMP. (°F)		MEASUREMENT LOCATION (INCHES)	MEASURED UNIFORMITY (PERCENT)
				A		A	B		
1	60	980	58.8	3106		2964	3025	-33.75	25.2
2	60	990	59.4	3106		2970	3036	-31.75	55.2
3	60	980	58.8	3095		-	3016	-29.75	78.8
4	60	1000	60.	3124		2982	3025	-27.75	86.8
5	60	1000	60.	3124		2930	3025	28.0	96.1
6	60	1000	60.	3144		2953	3025	30.0	94.3
7	60	1000	60.	3144		2947	3036	32.0	82.0
8	60	1000	60.	3153		2965	3064	34.0	60.0

A - MANUAL PYROMETER
B - THERMOGAGE PYROMETER

FIGURE 34



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72 INCH HEATER MODULE TEST SPECIMEN INCIDENT HEAT FLUX UNIFORMITY

- HEATER ELEMENT POWER = 53.1 KW
- STEADY STATE ANALYSIS
- GOLD COATED REFLECTORS ($\rho = 0.80$)
- ADIABATIC TEST SPECIMEN

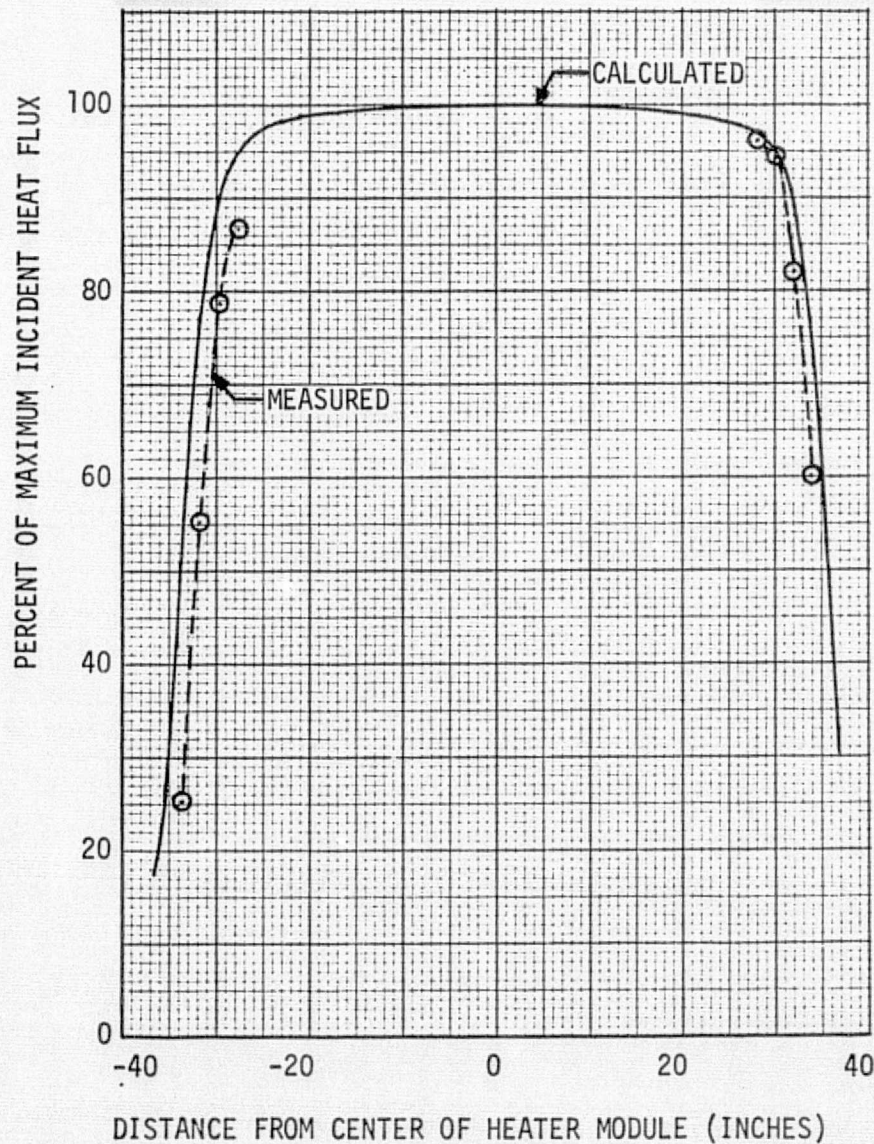
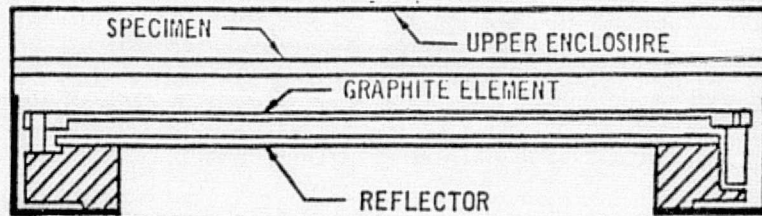


FIGURE 35

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ELECTRICAL RESISTIVITY OF 890S GRAPHITE

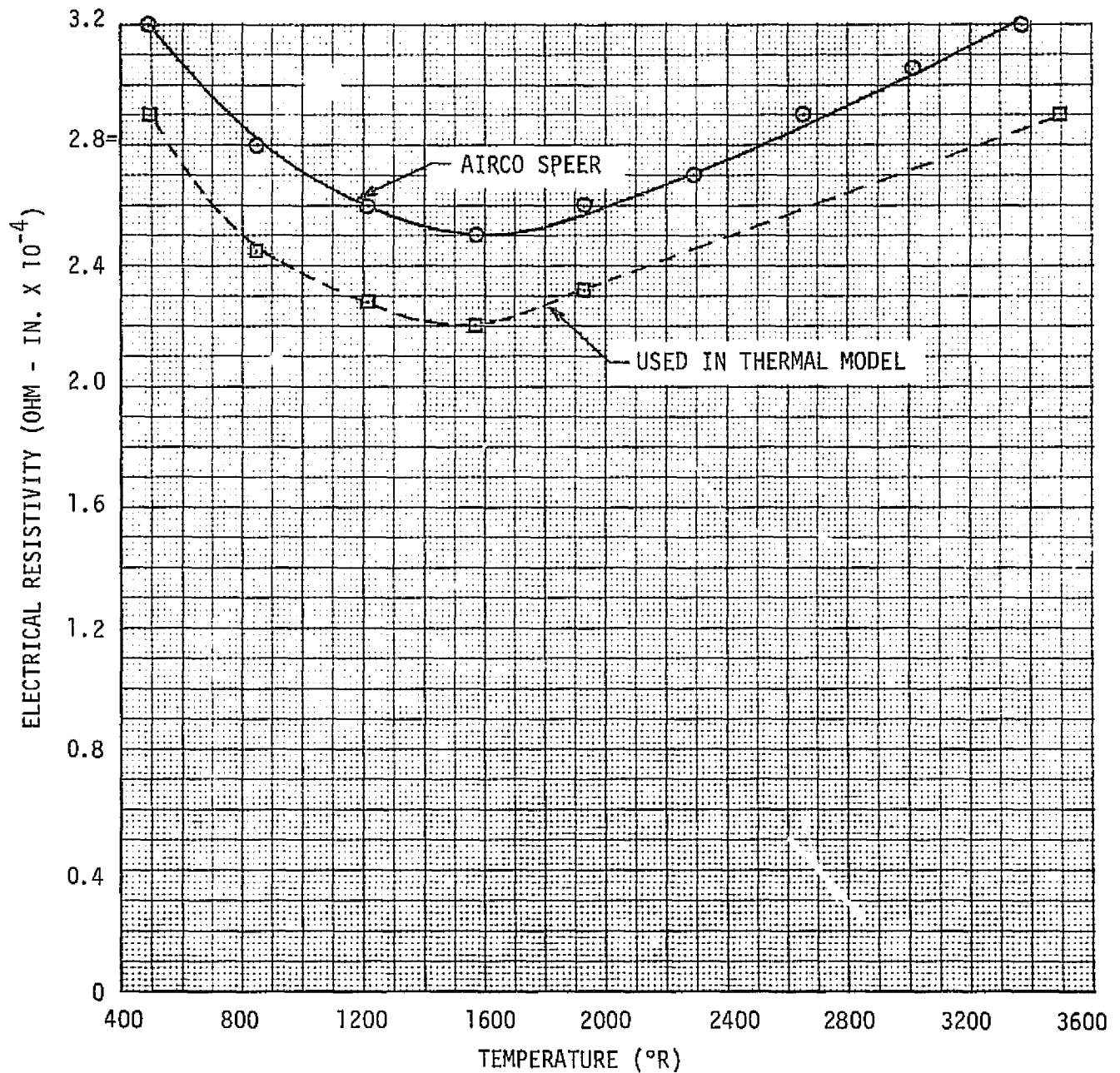
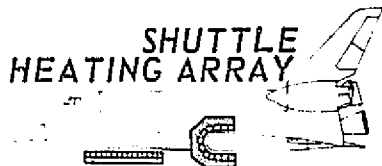


FIGURE 36



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a function of temperature. The solid curve is the "as advertised" resistivity of 890S by its supplier, Airco Speer. A Speer representative has stated that this curve is on the high side of the normal tolerance band. The dashed curve is the resistivity that is used in the thermal model. This curve is approximately 87% of the advertised curve and is representative of the nominal values of resistivity. Figure 37 is a comparison of measured and predicted performance test results as a function of input voltage. The predicted values were calculated using the updated features of the thermal model discussed above and compare favorably with the measured values. Figure 38 presents the predicted maximum heater element and test specimen temperatures as a function of power supplied to the heater elements. The calculated and measured incident heat flux distribution to the test specimen is shown in Figure 39 for a 60 volt input to the heater module. The uniformity measurements indicate the 85% incident heat flux uniformity can be achieved for a 60 inch test article (-28.5 to 31.5 inches). The calculated heater element and test specimen temperature distributions are shown in Figure 40. It can be seen that the element temperature varies less than 100°F over more than 60 inches. This means that the electrical resistivity varies little over the 60 inch length and explains the lack of improvement in the predicted uniformity.

An analytical study was made to determine the effect of contoured heater elements on incident heat flux uniformity. The standard heater elements are 0.42 inches thick for the 70 inches where significant heat generation occurs. The thermal model was changed to represent heater elements which have been shaved to 0.25 inch for the last 4 inches on the electrical (cooler) end. Figure 41 shows the predicted heater element and test specimen temperature distributions for standard heater elements and shaved heater elements. These temperatures are for an input potential of 60 volts. The shaved heater element has its peak temperature at the 0.25 inch/0.42 inch interface as opposed to the center of the elements for the standard elements. Also, shaving the elements increases its total electrical resistance, lowers the current, and lowers the element temperature at the center of the elements. The test specimen has its maximum temperature at its center for both the standard and shaved elements. The calculated incident heat flux uniformity is presented in Figure 42. The shaved elements extend the 85 percent uniform zone by approximately 2.5 inches. It appears that shaving the heater elements can provide greater uniformity.



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COMPARISON OF MEASURED AND PREDICTED PERFORMANCE OF THE 72 INCH HEATER MODULE

<u>Voltage</u>	<u>Amperage</u>		<u>Power</u>		<u>Element Temp</u>		<u>Specimen Temp</u>	
	Meas	Pred	Meas (KW)	Pred (KW)	<u>Meas</u>	<u>Pred</u>	<u>Meas</u>	<u>Pred</u>
					(°F)	(°F)	(°F)	(°F)
60	1000	979	60	58.7	3124	3121	3025	2976
55	900	919	49.5	50.5	2946	2975	2841	2832
45	780	794	35.1	35.7	2647	2656	2503	2516
37	690	688	25.5	25.4	2348	2367	2177	2227

FIGURE 37



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CALCULATED PERFORMANCE CHARACTERISTICS
OF THE 72 INCH HEATER MODULE

- VARIABLE ELECTRICAL RESISTIVITY
- GOLD COATED REFLECTORS ($\rho = 0.83$)
- HEAT TRANSFER TO BACK OF TEST SPECIMEN
- GRAPHITE TEST ARTICLE
- STEADY STATE ANALYSIS

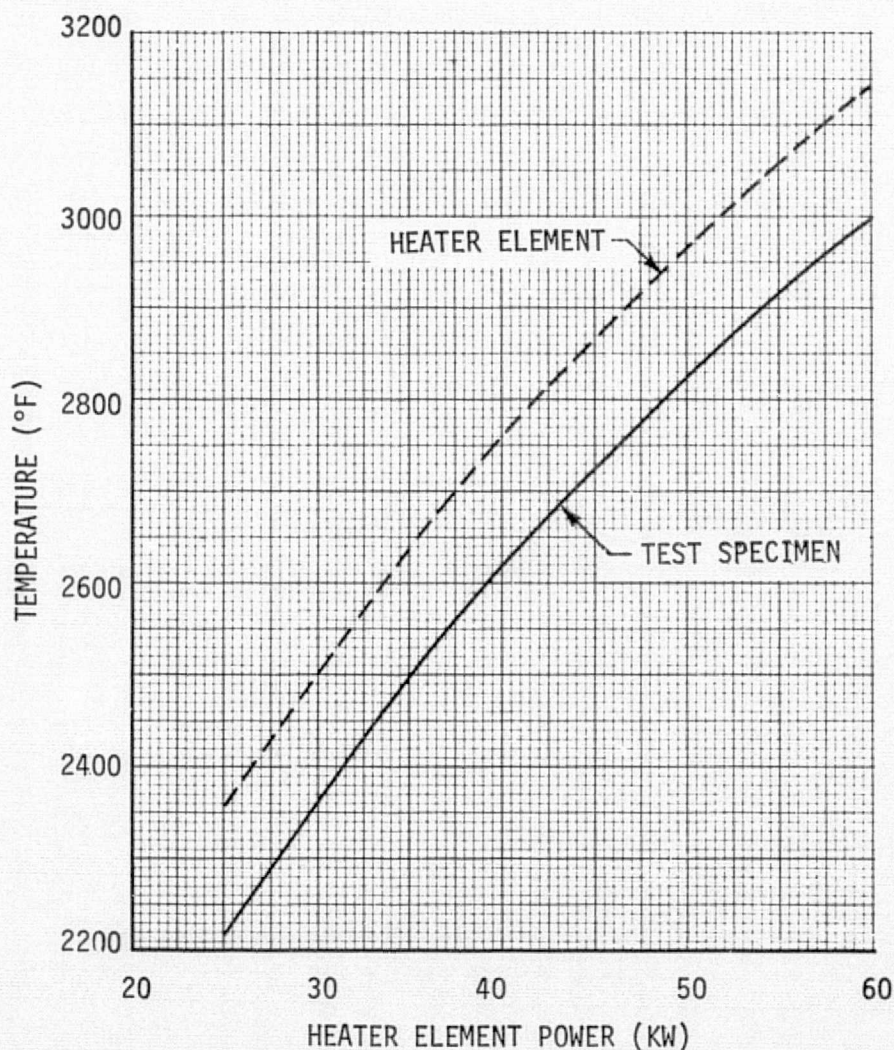
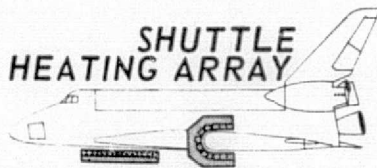


FIGURE 38



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72 INCH HEATER MODULE, TEST SPECIMEN

INCIDENT HEAT FLUX UNIFORMITY

- V = 60 VOLTS
- P = 58.7 KW
- GOLD COATED REFLECTORS ($\rho = 0.83$)
- STEADY STATE ANALYSIS

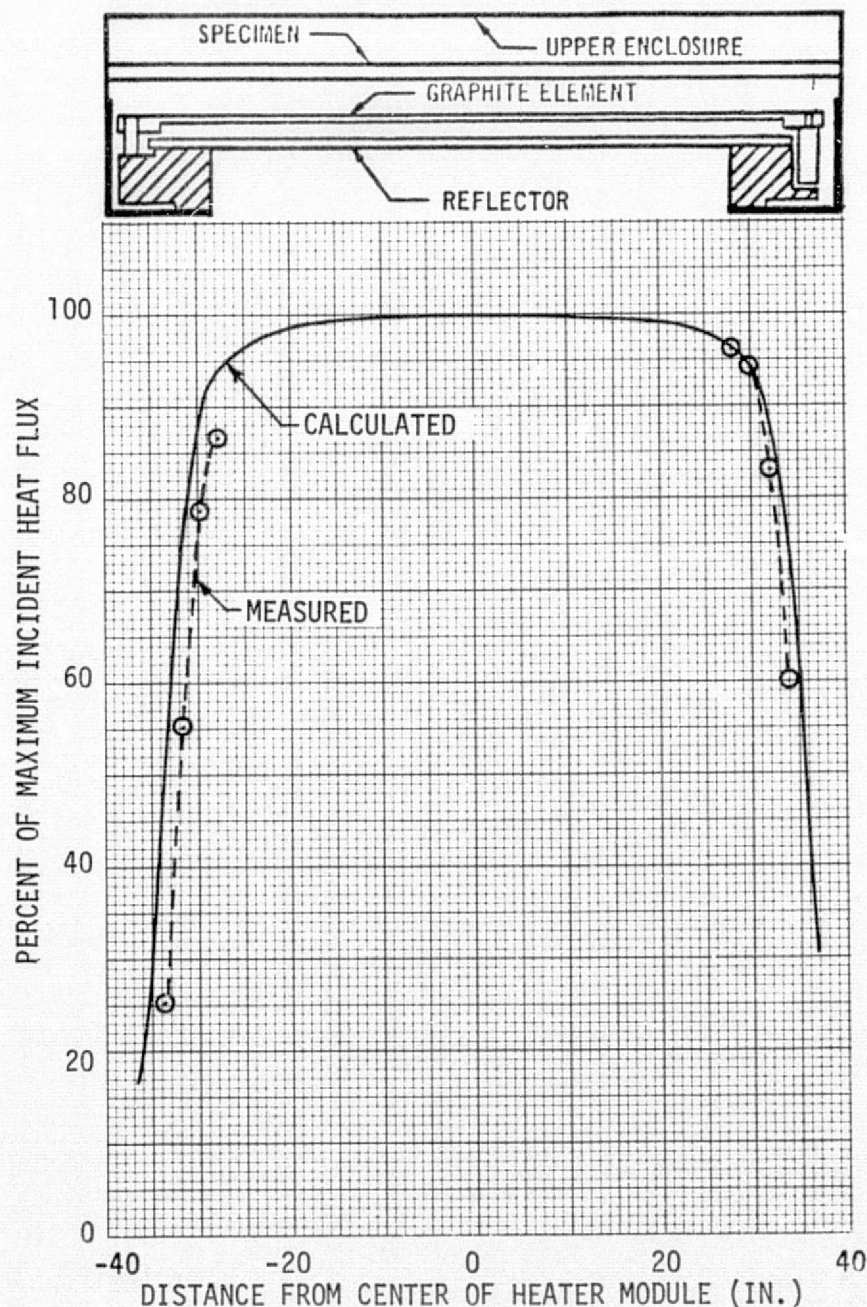
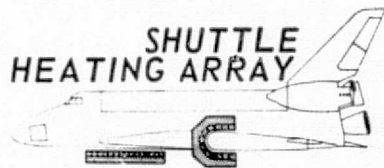


FIGURE 39



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72 INCH HEATER MODULE CALCULATED TEMPERATURE

- V = 60 VOLTS
- P = 58.7 KW
- GOLD COATED REFLECTORS ($\rho = 0.83$)
- STEADY STATE ANALYSIS

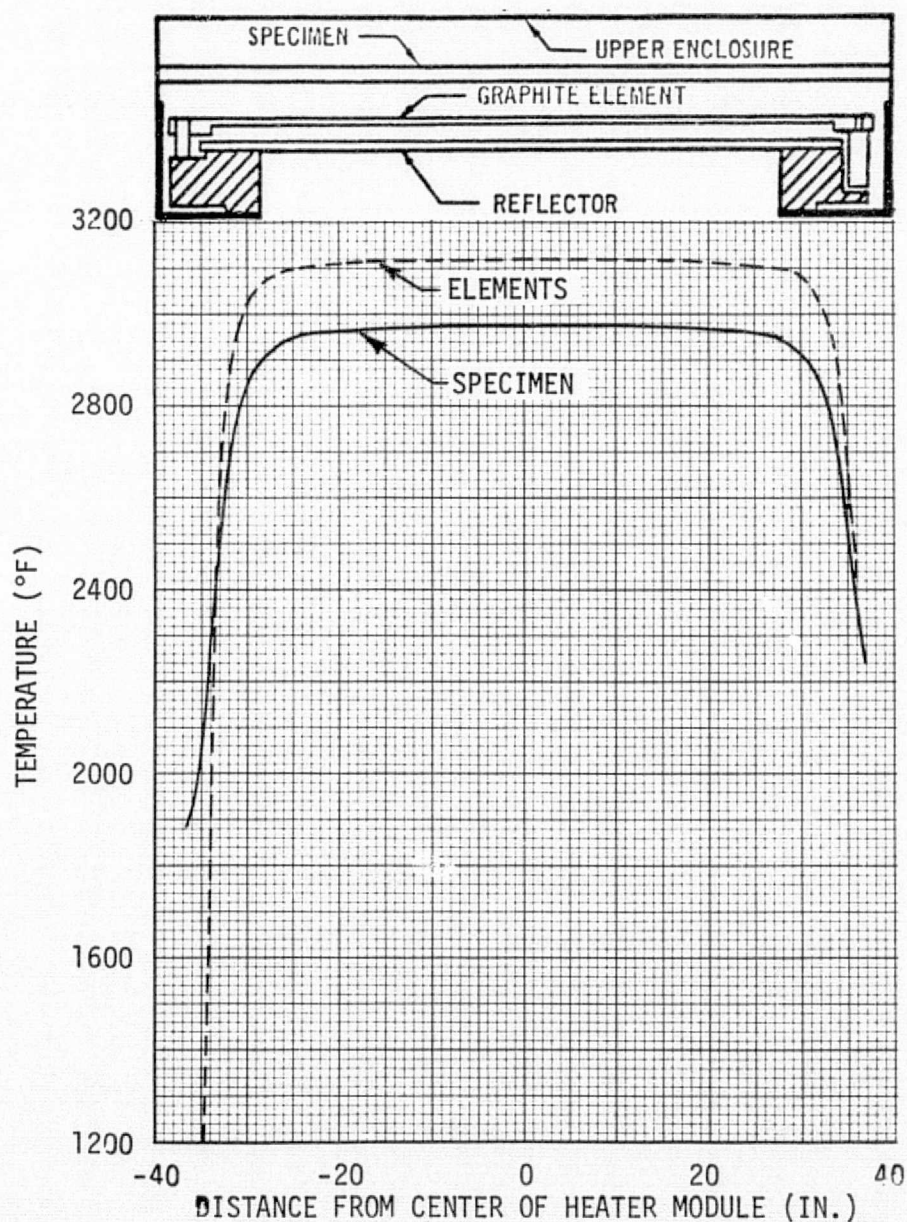
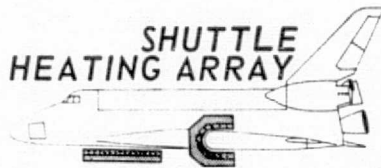


FIGURE 40



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PREDICTED 72 INCH HEATER MODULE TEMPERATURES WITH UNIFORM AND SHAVED HEATER ELEMENTS

- UNIFORM ELEMENT $t = 0.42$ IN.
- SHAVED ELEMENT $t = 0.42$ IN. EXCEPT $t = 0.25$ IN. FOR 4 IN. STARTING AT ELECTRODE END
- $V = 60$ VOLTS
- GOLD REFLECTORS ($\rho = 0.83$)
- STEADY STATE ANALYSIS
- VARIABLE HEAT GENERATION

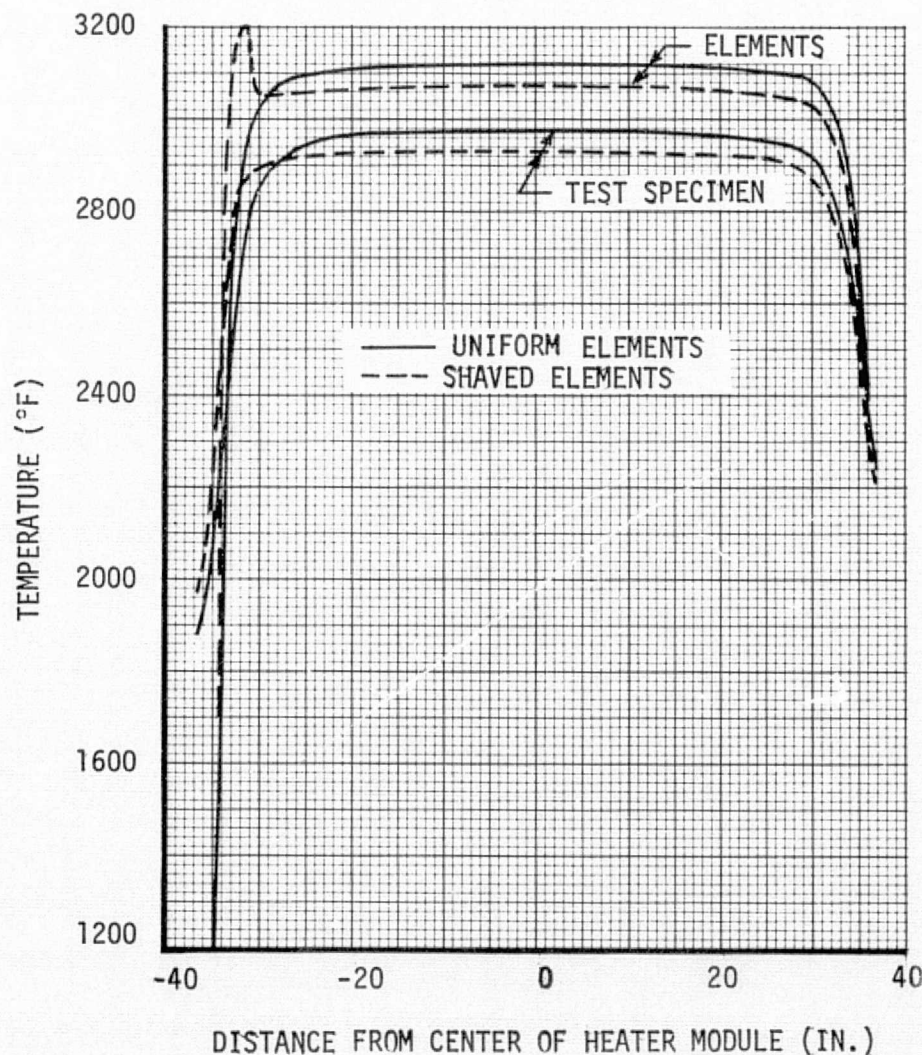
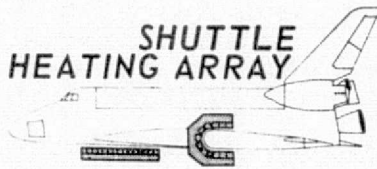


FIGURE 41



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PREDICTED UNIFORMITY OF 72 INCH HEATER
MODULE WITH UNIFORM AND SHAVED HEATER ELEMENTS

- UNIFORM ELEMENT $t = 0.42$ IN.
- SHAVED ELEMENT $t = 0.42$ IN. EXCEPT $t = 0.25$ FOR 4 IN. STARTING AT ELECTRODE END
- $V = 60$ VOLTS
- GOLD REFLECTORS ($\rho = 0.83$)
- STEADY STATE ANALYSIS
- VARIABLE HEAT GENERATION

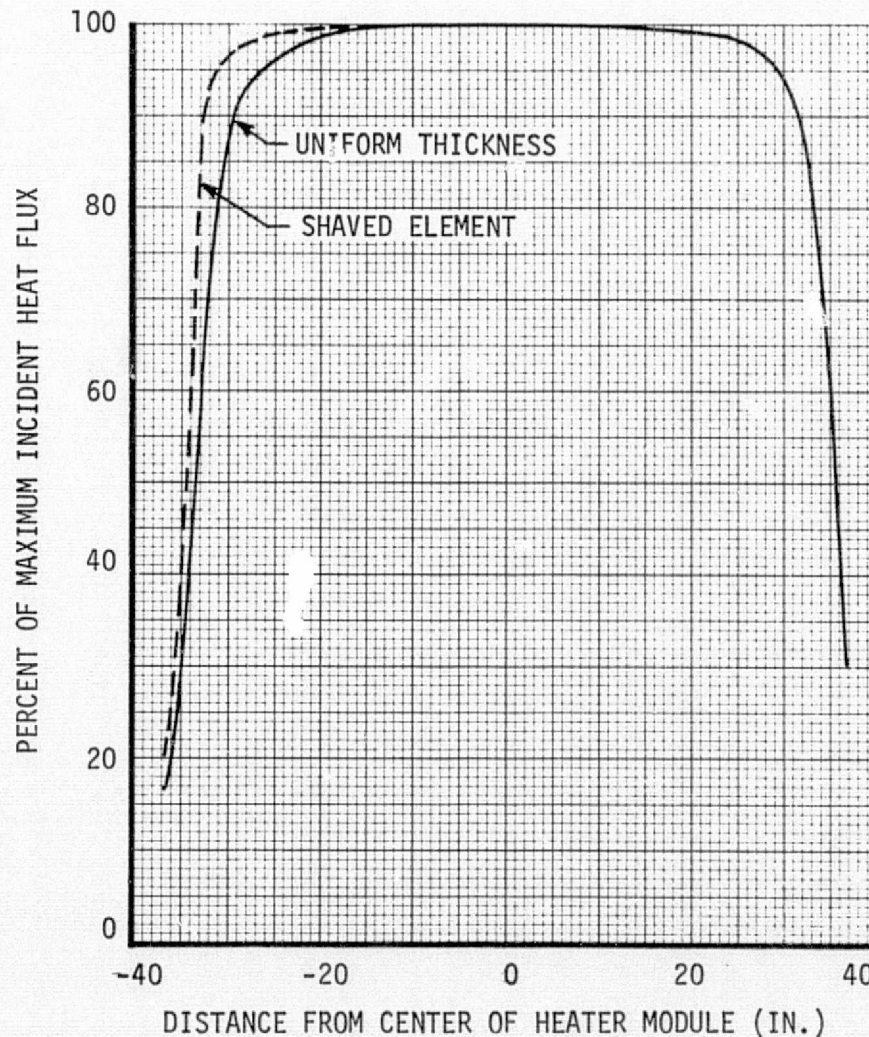
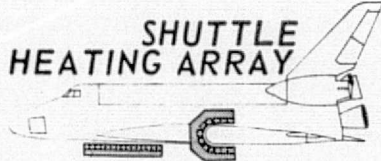


FIGURE 42



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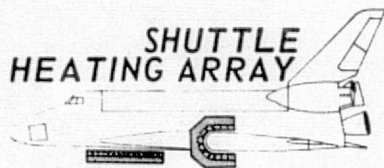
An analysis was performed to predict the performance provided by the 72 inch heater module at low input voltage. Figure 43 presents the calculated heater element and test specimen temperature distributions for input potentials of 10 and 15 volts. These predictions were made for standard heater elements (0.42 inch thick) which were designed to operate at temperatures above 3000°F. The predicted heat flux uniformity is shown in Figure 44. The uniformity is lower for these low temperature (610°F and 1040°F specimen temperatures) operations than for the high temperature operations for which the heater was designed.

4.4.3 Electrical Calculations - The thermal analyses defined the heated length and width of the heater along with the power required. Compatibility with ignitron power supplies and 4:1 stepdown transformers establishes the usable voltage while the basic design of the heater assembly defines the electrical arrangement of two hairpin type elements in parallel. The only parameters to be calculated are the element thickness and the resulting current. An example of this calculation is shown in the following:

Power per module	= 110 KW
Voltage per element	= 80 volts
Heated length	= 70 inch
Width per strip	= 0.8 inch
Resistivity	= 2.8×10^{-4} ohm-inch
Power per strip	= 27.5 KW
Voltage per strip	= 40 volts
Current = $\frac{27.5 \times 10^3}{40}$	= 690 amps (current per element, 1380 amps per module)
Resistance per strip = $\frac{40}{690}$	= .058 ohms
Thickness = $\frac{2.8 \times 10^{-4} \times 70}{0.8 \times .058}$	= .42 inch

This calculation is for a 72 inch heater module and a similar calculation for the 48 inch module using a power level scaled by the ratio of the heated lengths resulted in a thickness of .182 inch and a total current of 900 amp at 80 volts.

4.4.4 Cooling Calculations - Calculations and operational experience prior to this contract allowed the reflector panels to be designed according to a heated area correlation; and therefore little, if any, computations were done to support their design. This fact coupled with the development testing on the 36-inch prototype heater module offered a high confidence level for the successful operation of the 72 inch and 48 inch heater module cooling systems.



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PREDICTED LOW TEMPERATURE 72 INCH HEATER MODULE TEMPERATURES WITH STANDARD HEATER ELEMENTS

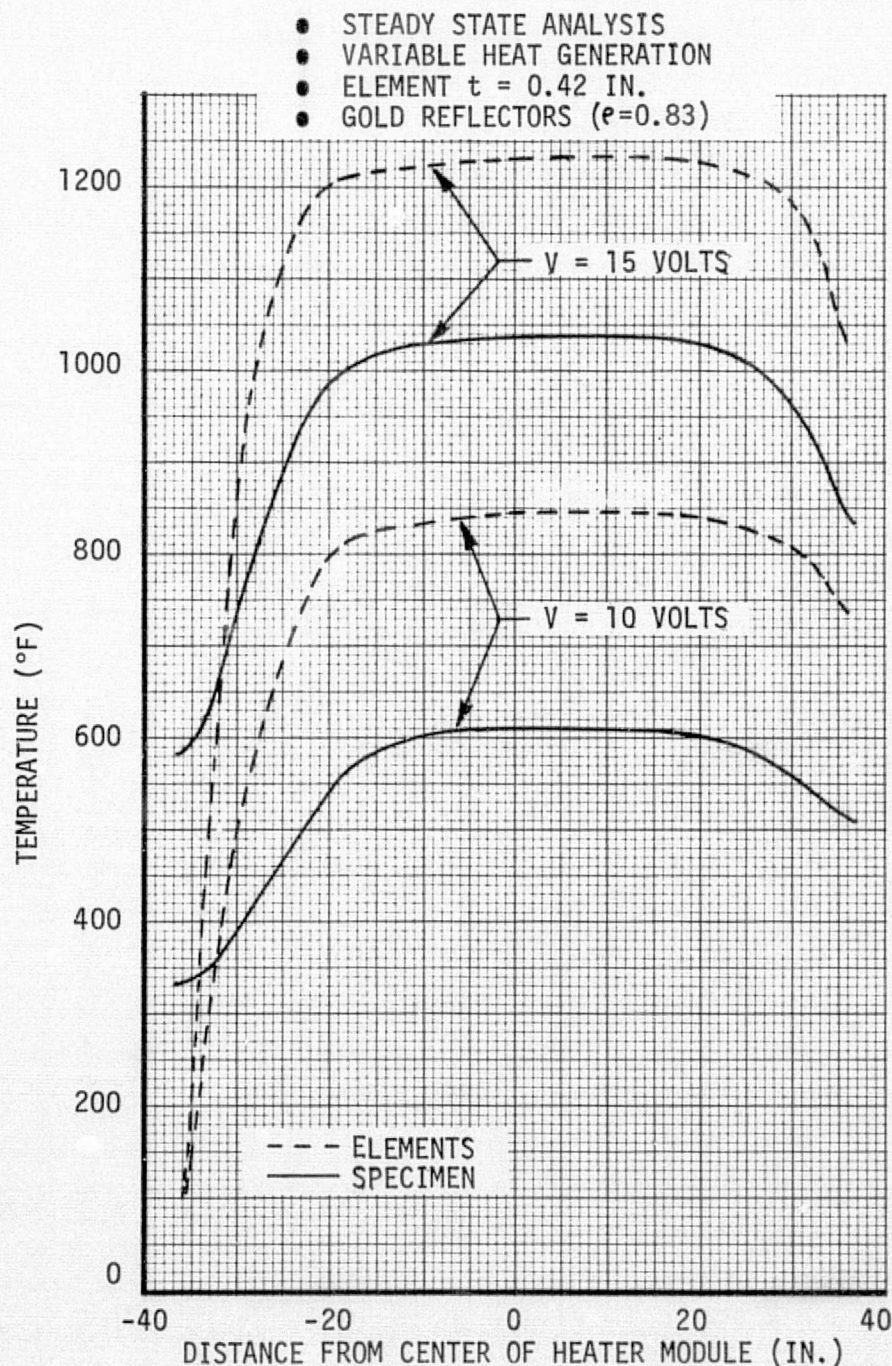
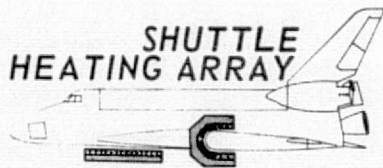


FIGURE 43



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PREDICTED LOW TEMPERATURE UNIFORMITY OF 72 INCH
HEATER MODULE WITH STANDARD HEATER ELEMENTS

- STEADY STATE ANALYSIS
- VARIABLE HEAT GENERATION
- ELEMENT $t = 0.42$ IN.
- GOLD REFLECTORS ($\epsilon = 0.83$)

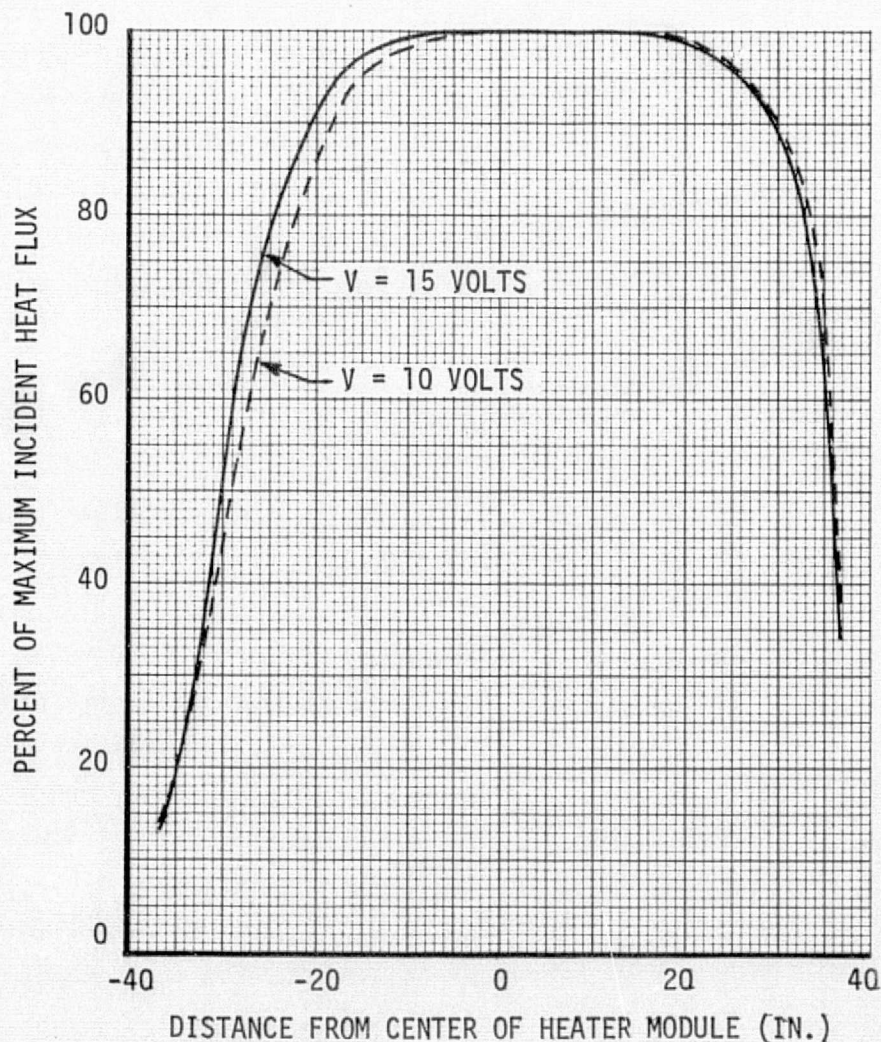


FIGURE 44:



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The rest of the cooling system external to the heater module itself offered a somewhat greater concern as regards pressure drop, flow distribution, and the possible variables introduced by the use of a glycol-water mix rather than plain water.

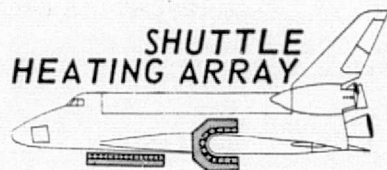
To evaluate the effect of the use of glycol, the heat transfer properties for a 50% glycol-water mix were compared to those for water at the same representative temperature. In addition, the capability of each to absorb heat and to generate an adequate heat transfer coefficient was evaluated by a ratio comparison of the key heat transfer equations. The results of this comparison indicated that the glycol-water mix would transfer the heat from the reflectors 6% more efficiently but in so doing would rise in temperature 15% more than water for the same total heat load.

In evaluating the suitability of 4 inch pipe for the array supply and return, the question of flow distribution to the modules arose. An analytical model was set up consisting of twenty-two 48-inch heater modules in parallel connected to 4-inch supply and drain headers arranged such that the water entered and exited on the same end of the array. The computation is one which determines the degree of maldistribution of flow by comparing frictional pressure drop effects to momentum pressure rise in the supply and return headers. The result of this evaluation was that a maldistribution of approximately 1% would result and that this was entirely within the limits of acceptability.

To size the hoses required to supply coolant to the heaters from the support structure manifolds, a conventional pressure drop analysis was made including frictional pressure drop in the hose, several entrance and exit losses and the loss through the quick-disconnect fittings. This analysis resulted in the specification of 3/4 inch hoses and quick-disconnects for the supply and return of each heater module.

4.5 DEVELOPMENT TESTING - A development test setup was built including a 72-inch heater assembly, a 72-inch test article and all associated plumbing and instrumentation. Figures 45 and 46 are views of the heater module installed in the 5.5 foot vacuum chamber. Note that the graphite heater elements are not installed in the heater. In Figures 47 and 48 the elements have been installed.

A water management program was performed, and selected circuits restricted to improve the flow balance. The flow characteristic of the 72-inch heater assembly is approximately 25 gpm at a 60 psi pressure drop with the coolant flow distribution shown in Figure 49. Preliminary checkout testing of the 72-inch heater assembly was done first. During this phase of the testing, persistent failure of the graphite lever on the expansion end occurred. Additional development tests and more refined



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72 INCH HEATER MODULE DURING PERFORMANCE TESTING (HEATER ELEMENTS NOT INSTALLED)

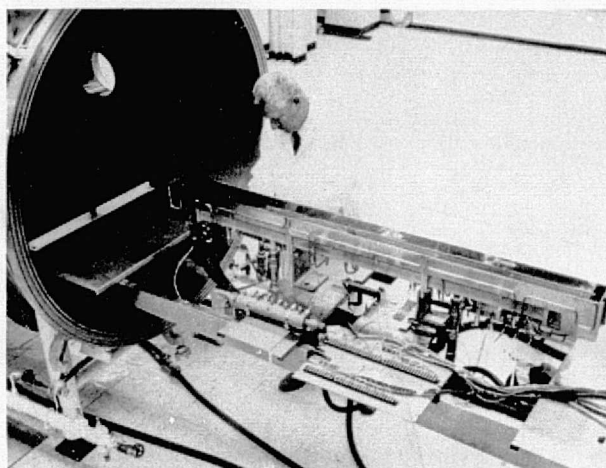


FIGURE 45

END VIEW OF 72 INCH HEATER MODULE (HEATER ELEMENTS NOT INSTALLED)

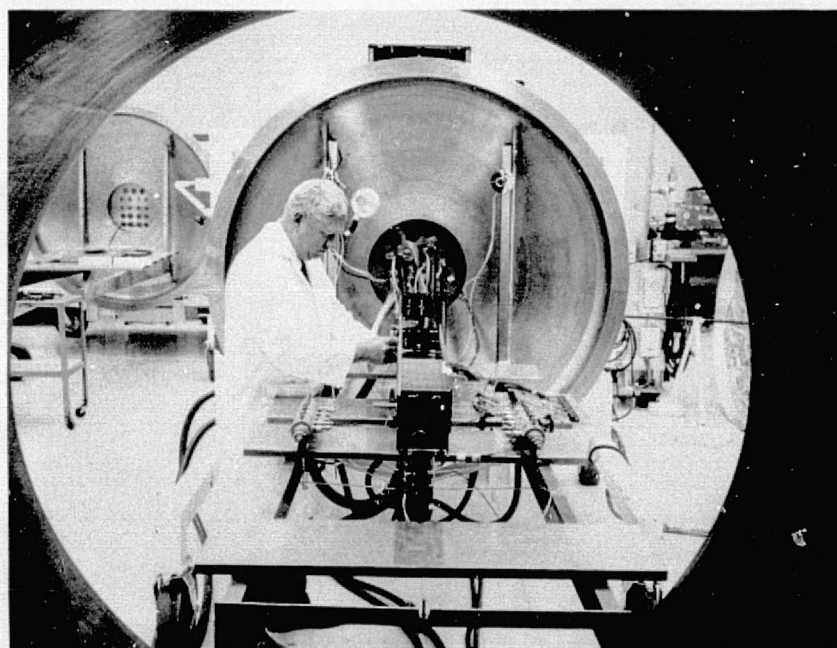
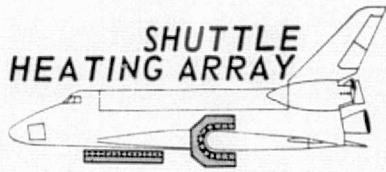


FIGURE 46



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END VIEW OF 72 INCH HEATER MODULE DURING PERFORMANCE TESTING

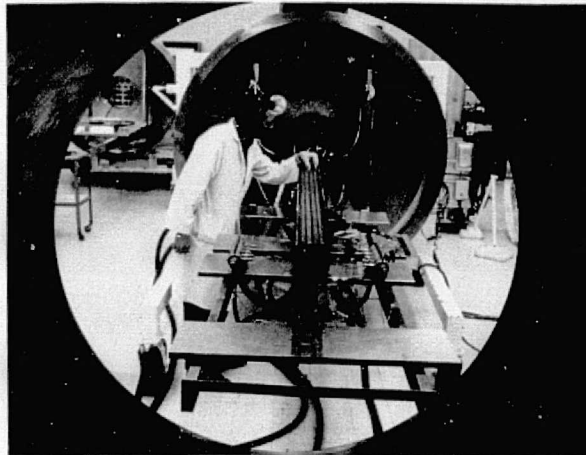


FIGURE 47

72 INCH HEATER MODULE DURING PERFORMANCE TESTING

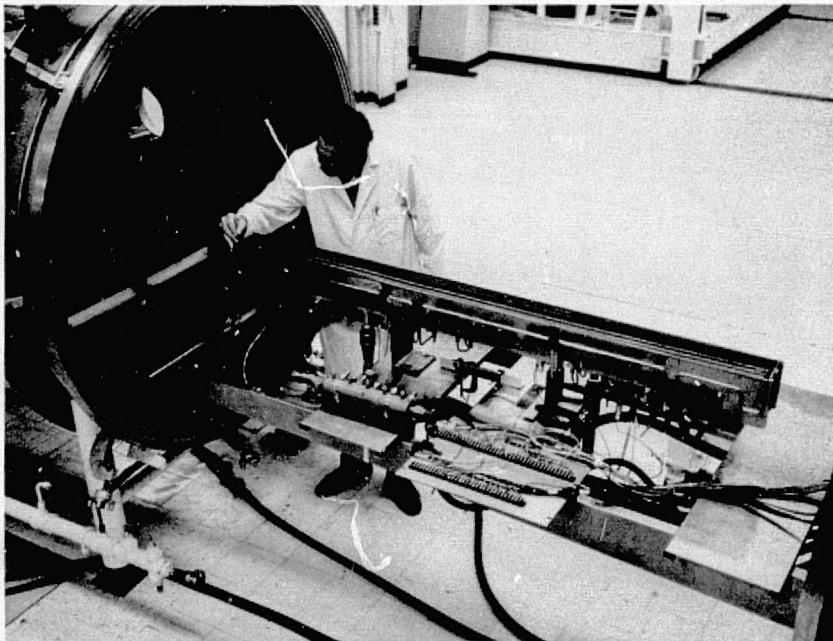


FIGURE 48

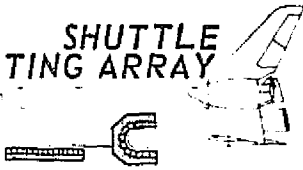


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COOLANT FLOW DISTRIBUTION

Coolant Circuit	Flow Rate @ 60 psi ΔP (gpm)	Percent of Total (%)
T-055430-3 Side Reflector Assy.	2.31	8.71
T-055430-5 Side Reflector Assy.	2.20	8.29
T-055430-7 Bottom Side Reflector Assy.	1.93	7.27
T-055430-9 End Reflector Assy.	1.04	3.92
T-055430-13 (2) plus -15 Electrode Blocks	2.37	8.93
T-055431-11 (A1) Block Assy.	0.48	1.81
T-055431-3 Bottom Reflector Assy.	1.95	7.35
T-055431-5 Side Reflector Assy.	2.44	9.20
T-055431-7 Side Reflector Assy.	2.37	8.93
T-055431-11 (A2) Block Assy.	0.45	1.70
T-055431-11 (A3) Block Assy.	0.46	1.73
T-055432-3 Side Reflector Assy.	2.31	8.71
T-055432-5 Side Reflector Assy.	2.19	8.25
T-055432-7 Bottom Reflector Assy.	1.95	7.35
T-055432-9 End Reflector Assy.	1.00	3.77
T-055432-13 (2) Support Block Assy's.	1.08	4.07

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calculations indicated that the tapered peg was over stressed due to the thermal expansion of the heating element. The problem was resolved by redesigning the lever to provide a larger cross section with further testing of the new design resulting in no more failures. Figure 50 shows the original lever tested, the intermediate levers tested, and the increased cross section lever which functions properly. Also, during checkout testing, it was noted that high current electric field effects caused the two center graphite strips to pull together. A graphite spacer with an "I" cross-section was installed between these strips to correct this condition. This graphite was subsequently replaced with a boron nitride spacer, as explained in a following paragraph.

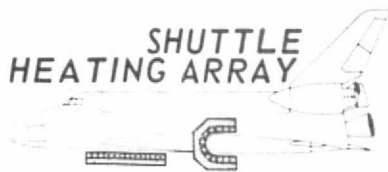
The maximum temperature requirement was satisfied by operating the heater for 10 minutes at a test article surface temperature above 3200°F. This condition was achieved with a power input to the heater of 87 KW with operation at 75 volts and 1160 amps.

Testing to determine the heat flux uniformity at each end of the 72-inch heater assembly was initiated. The heater was operated at 60 volts and 1000 amps with the resulting test specimen temperature of 3000°F. The heat flux indicated by a calorimeter in each of four positions on each end of the test article was compared to that from a calorimeter located 14 inches from the heater center. The results of this testing are discussed in Section 4.4.2.4 dealing with the thermal analysis.

Testing of the 72-inch configuration was concluded with heater operation at low pressures, and operation with the heater oriented on its side.

To demonstrate the heater's capability to function properly at low environmental pressures, the heater was operated at 75 volts and specimen temperatures exceeding 3200°F while the chamber pressure was decreased in steps from 100 torr to 0.5 torr. No difficulty was experienced.

The heater was also operated at its design temperatures while oriented on its side, as shown in Figure 51. Some of the heaters will be so oriented in the leading edge test configuration. It was found that the heating elements tended to sag excessively and take a permanent set while operating in this manner. Successive operations at high temperatures (3200°F or greater) resulted in the elements eventually sagging against the bottom reflector or each other. Spacers were fabricated from boron nitride, a machinable high temperature material with excellent high temperature electrical resistivity. These spacers were placed between each pass of the elements,



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EXPANSION LEVERS TESTED DURING HEATER CHECKOUT

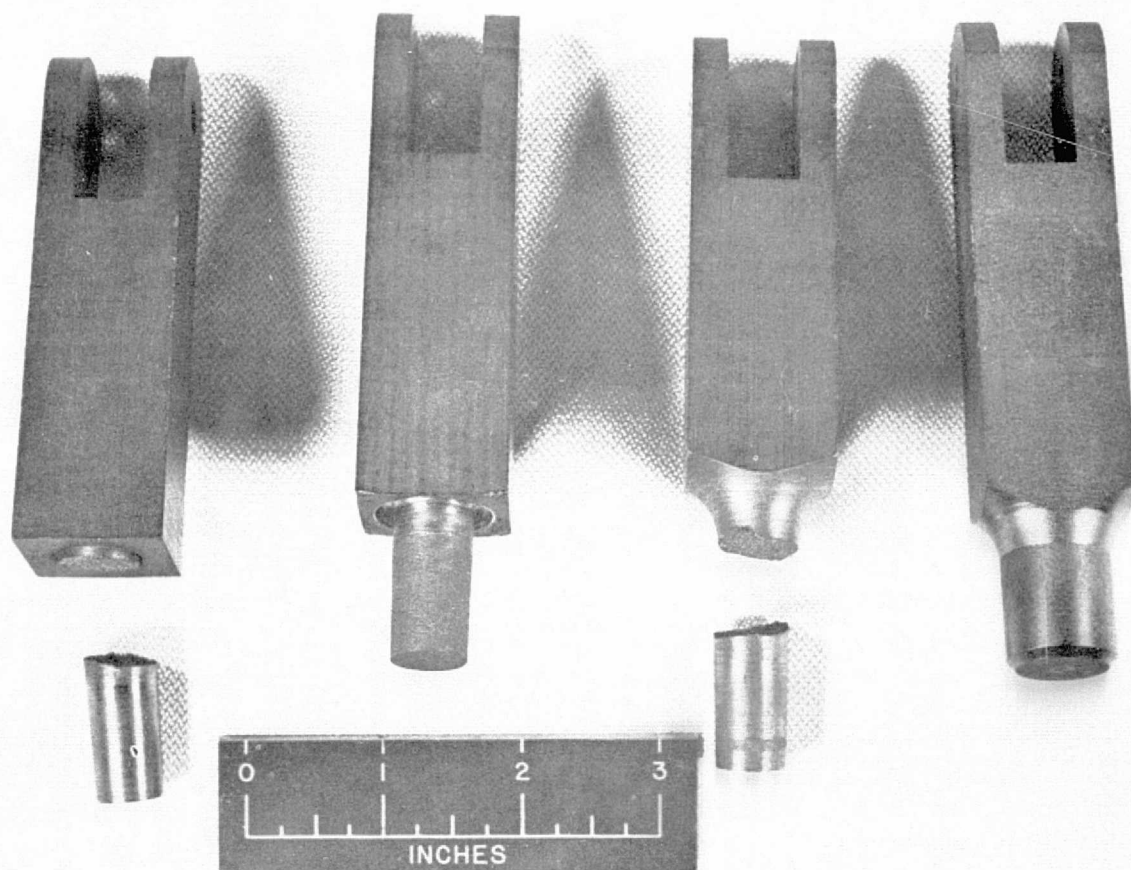
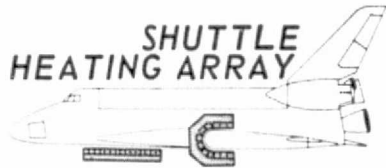


FIGURE 50



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72 INCH HEATER MOUNTED ON ITS SIDE DURING PERFORMANCE TESTING

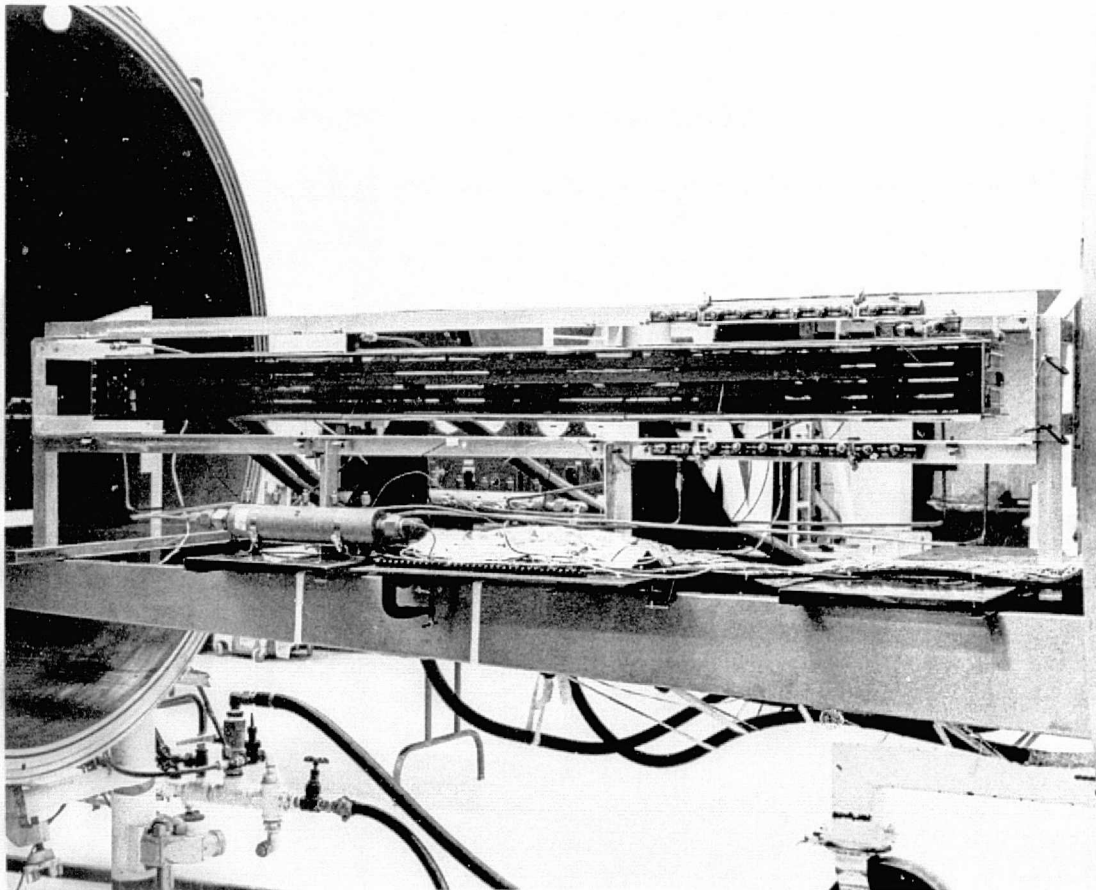


FIGURE 51

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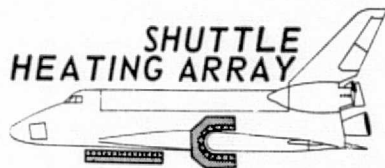
(replacing the graphite spacer) and between the element and the lower reflector. Subsequent heater operation indicated the spacers cured the problem, and therefore were incorporated in the heater design for operation with the heater in other than an upright configuration.

The heater was then placed in the 48-inch configuration, and subjected to all the tests performed on the 72-inch heater. Figures 52 and 53 show the heater in the 48-inch configuration arranged on its side in the test setup. The water flow characteristic of the heater in the 48-inch configuration is 20 gpm @ 60 psi pressure drop.

The maximum temperature requirement was satisfied by operating the heater for 10 minutes at a test article surface temperature above 3200°F. This condition was achieved with a power input to the heater of 68 KW with operation at 80 volts and 850 amps.

The heater was also operated at 60 volts and 700 amps with a resulting test specimen temperature of 2900°F. Following these tests, the heater was operated on its side, and at low pressures just as the 72-inch heater. No problems arose and the sagging of the elements did not occur with the 48-inch elements. Hence no spacers are required for the 48-inch heater configuration.

4.5.1 Side by Side Tests - To insure the proper function of the entire heating array, two 72 inch heater modules were installed on the support structure and successfully operated at a nominal power settings to achieve a specimen surface temperature of 3200°F for 10 minutes. The test was performed in a nitrogen environment at ambient pressure. Figures 54 and 55 show the side by side test setup. The two modules were operated using two 4:1 stepdown transformers. Tests were conducted with in-phase and out-of-phase heater module current with no ill effects. This demonstrated the overall operation of the heating array prior to delivery of the unit to NASA-JSC.



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**48 INCH HEATER MOUNTED ON ITS SIDE
DURING PERFORMANCE TESTING**

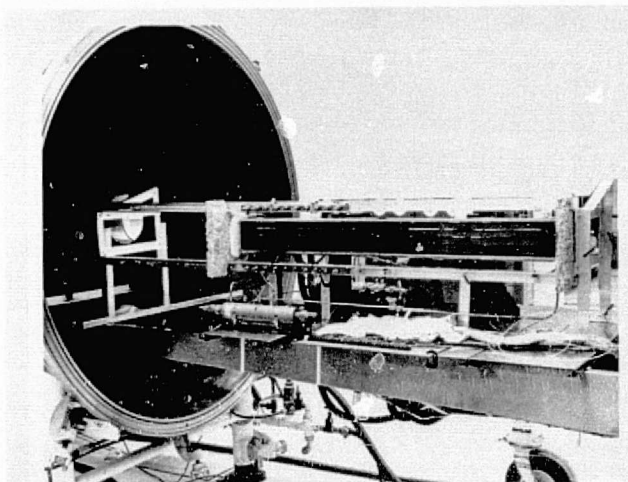


FIGURE 52

**48 INCH HEATER MOUNTED ON ITS SIDE DURING
PERFORMANCE TESTING (OVERHEAD VIEW)**

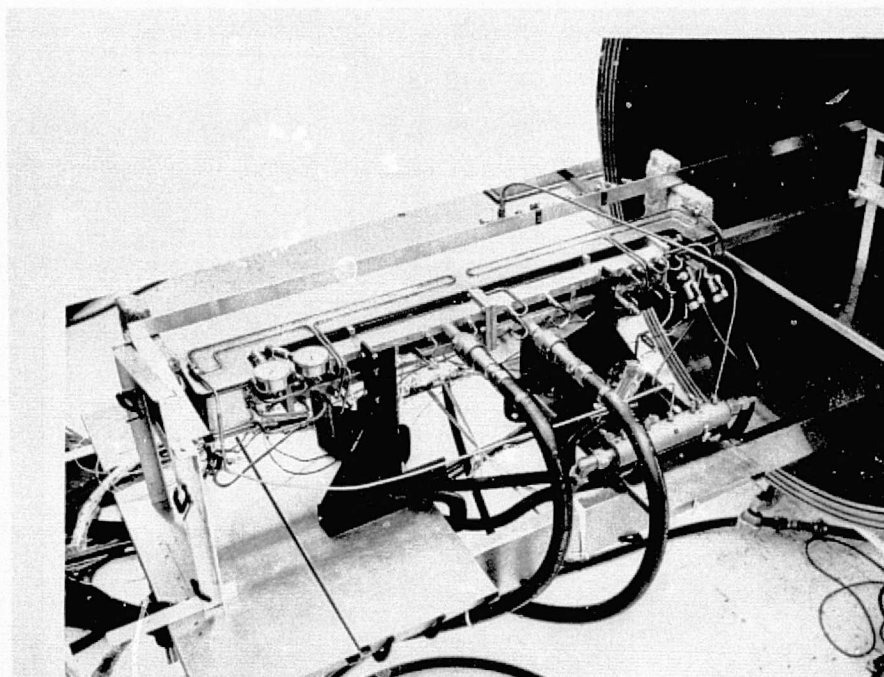
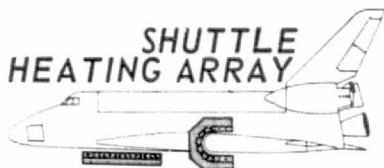


FIGURE 53



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SIDE BY SIDE HEATER MODULE TEST SETUP

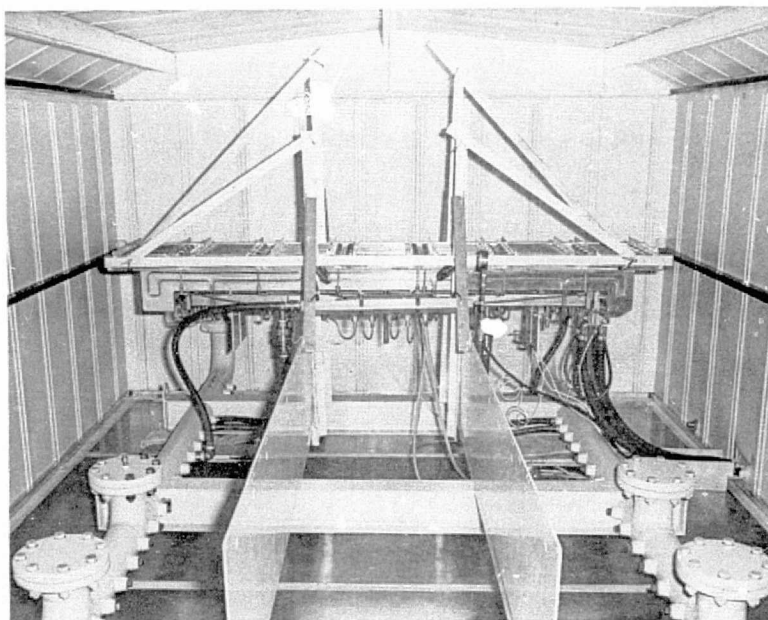


FIGURE 54

VIEW OF HEAT MODULES DURING SIDE BY SIDE TEST

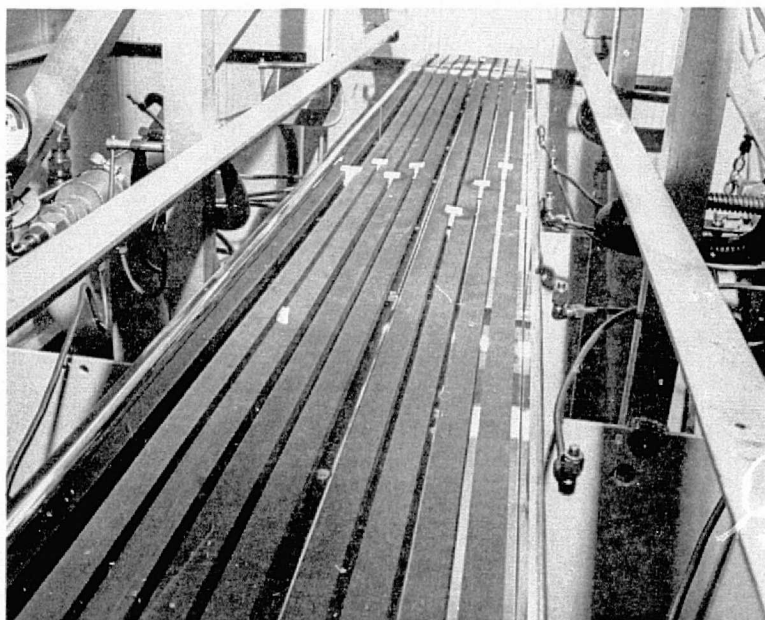


FIGURE 55



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4.6 Auxiliary and Support Equipment - The following is a list of the minimum amount of auxiliary equipment required to properly support the operation of the Leading Edge and Flat Surface Heating Array. This equipment is assumed to be installed at and furnished by NASA-JSC.

Electrical Equipment

- o Ignitron power controllers - Research Incorporated (RI) Model 8129, 440 VAC, 400 amps max. - 1 required per heater.
- o Function generators - 1 unit per heater.
- o Temperature controllers - 1 unit per heater.
- o Stepdown transformers 480/120 VAC, 100 KVA - 1 unit per heater.
- o Electrical cables from ignitron power controllers to primary of stepdown transformers, 400 amps per channel.
- o Water-cooled wires from secondary of stepdown transformers to vacuum chamber feed-throughs, 1600 amps per wire, 2 wires per heater.
- o Water-cooled wires from vacuum chamber feed-through to heater, 1600 amps per wire, 2 wires per heater.

Vacuum Equipment

- o Ten foot diameter vacuum chamber.
- o Chamber pumping system.
- o Chamber pressure readout equipment and controls.
- o Instrumentation feed-throughs
 - Control feedback
 - Temperature monitors
 - Voltage monitors
 - Coolant interlock controls
- o Coolant feed-throughs, 4 inch NPT
- o Electrical feed-throughs 1600 amps max, 2 per heater
- o Inert gas feed-throughs for chamber purge gas.

Inert Gas System

- o Inert gas supply to vacuum chamber feed-throughs.
- o Throttling valve for chamber purge gas.

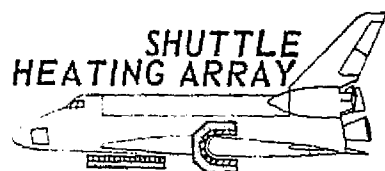
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Coolant System

- o Closed loop coolant system using glycol-water capable of heat dissipation of 4.2 Mw max.
- o Piping from vacuum chamber feed-throughs, 4 inch NPT supply and return.
- o Piping from vacuum chamber feed-throughs to heater support structure, 4 inch NPT supply and return.
- o Shutoff valves.
- o Pressure gauges.
- o Flowmeter.

Instrumentation

- o Temperature monitoring thermocouples, as required.
- o Data acquisition system.



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5.0 OPERATIONAL CHECKOUT

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5.0 OPERATIONAL CHECKOUT

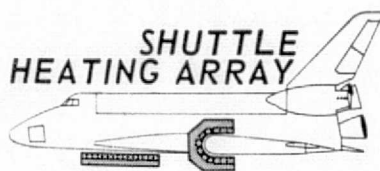
Each heater module was subjected to an operational checkout in our heater facility prior to shipping the unit to NASA-JSC. This checkout demonstrated that each unit was functionally operational, and capable of achieving and operating at design temperatures.

5.1 Test Description - A test article of sufficient length and width to cover the heated area of a 72 inch heater module (about 5 x 75 inches) was designed and fabricated prior to completion of the engineering model. The 72 inch test article consists of a water-cooled box containing an appropriate type and thickness of high-temperature insulation, with a 1/4-inch thick graphite plate covering the insulation. Heat flux sensors, mounted flush with the surface of the graphite plate at several appropriate locations, were used to map the heat flux uniformity near the ends of the heater modules. The test article is shown in Figure 56.

The first heater module to undergo testing was the 72 inch engineering model. Following final assembly, a water management program was performed on this unit. All necessary coolant circuit modifications and/or restrictors were incorporated in the production models.

Following the water management program, an experimental program was initiated using the engineering model to verify the integrity of the overall design in achieving the performance goals set forth under the development contract (NAS9-13544). These tests included heat flux uniformity mapping near the ends of the heater, operating the heater with a 3200°F specimen surface temperature, and establishing voltage-current relationships for both 48 and 72 inch configurations. All design deficiencies uncovered during these performance tests were corrected on the engineering model, and testing resumed to prove the soundness of the design. The details of this testing are discussed in paragraph 4.5.

As each production heater unit was assembled, it was installed in the same setup employed with the engineering model and given a functional checkout to verify the structural integrity of the manufactured components. The modules were serialized and a log sheet prepared for each unit. The results of the tests were recorded, and copies of these records accompanied the heater modules. The test results were also recorded in the Operation, Maintenance and Repair Manual (MDC Report E1234). These log sheets should be a standard reference for that particular heater module and can be utilized to detect abnormalities in the units at some future date.



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TEST ARTICLE FOR PERFORMANCE TESTING OF 72 INCH HEATER MODULE

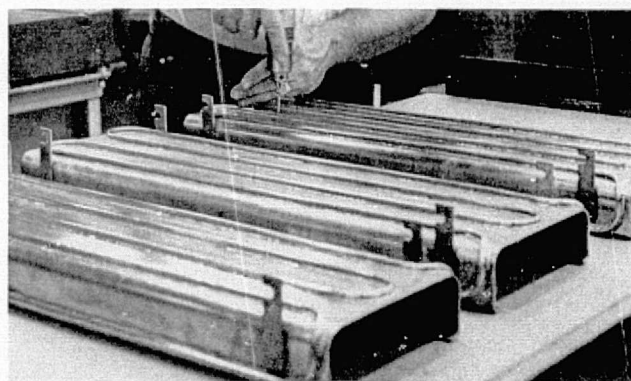
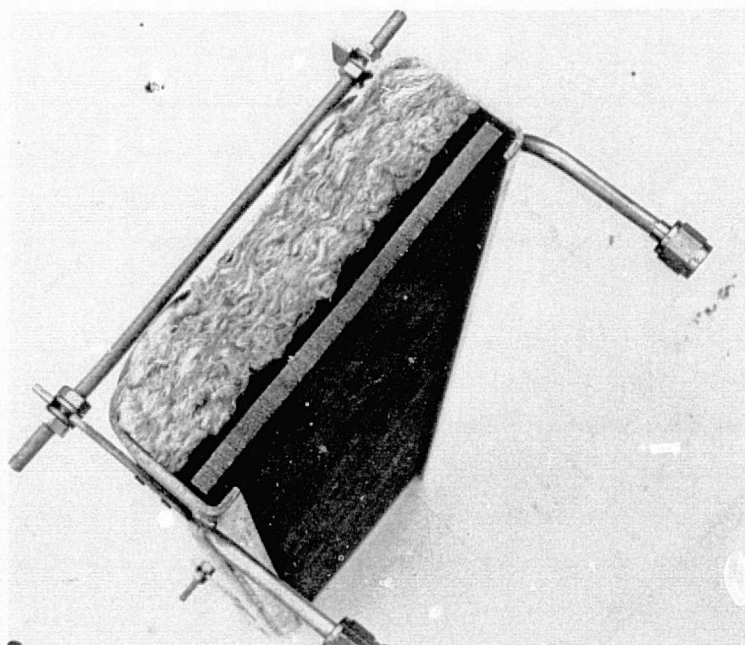
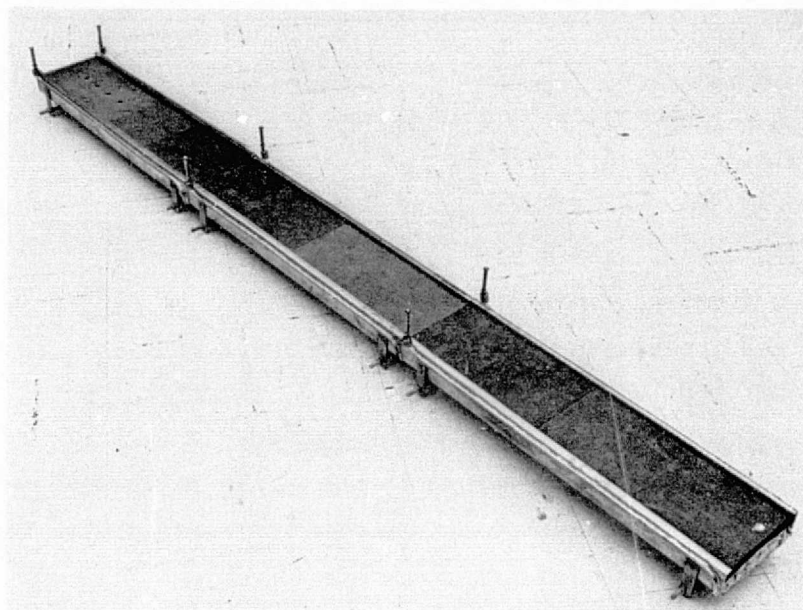
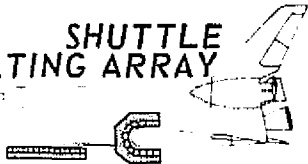


FIGURE 56



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Each production module received the following checks:

Leak Check - Pressure - The coolant system was pressurized to 150 psi (1.5 times the design operating pressure), and all seals and passages checked for leakage.

Insulation Leakage Resistance Test - An Evershed megger was used to measure the magnitude of the heater module internal insulation resistance.

High Voltage Breakdown Test - The breakdown voltage of the heater circuit was measured with an Associated Research Hypot insulation tester. The leakage current was set at a constant 0.5 milliamperes to obtain comparison between units.

Leak Test - Vacuum - The heater was tested for water leakage with the unit in a vacuum environment (less than 0.1 torr) and approximately 100 psi water pressure applied to the coolant circuits.

Water Flow Rate - The water flow rate through the heater coolant system was verified by measuring the pressure drop across the system. This data can be used to detect clogging of water passages during routine maintenance before the module sustains serious damage.

Operational Checkout - The 72 inch test article was mounted over the heater module for the operational checkout. The tests were conducted in an inert environment (gaseous nitrogen) at a reduced pressure. Power was applied to the heater to increase the specimen surface temperature to 3200°F, as read with the heater module's pyrometer. This condition was maintained for 10 minutes, allowing for stabilization of all parameters. Data was recorded under this condition while the module was kept under visual observation.

Following this high temperature checkout, the heater unit was removed from the test setup and thoroughly examined for indications of abnormal behavior, the gold reflectors cleaned, and the unit prepared for shipment. All data was entered in the unit's log sheet.

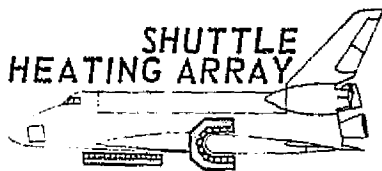
5.2 Test Results - The results of the operational checkout testing are summarized in Figure 57 for all 22 heater modules and seven absorber modules. It can be seen from this data that the performance of all the modules is essentially identical and also quite similar to the performance of the engineering model used during the development tests described in paragraph 4.5.



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HEATER-ABSORBER MODULE LOG SHEET SUMMARY

Part Number	S/N	Operational Checkout			
		Water @ 60 psi ΔP (gpm)	Specimen Temperature (°F)	Volts	Amperes
T-055429-1	01	24.78	3256	65	1000
	02	24.13	3289	65	990
	03	24.22	3200	70	1100
	04	25.16	3200	68	1060
	05	24.49	3200	65	1000
	06	24.14	3200	66	1020
	07	24.51	3221	66	1020
	08	24.33	3214	65	1010
	09	24.55	3233	65	1010
	10	24.60	3206	67	1040
	11	24.51	3200	70	1100
	12	24.82	3207	70	1100
T-055429-3	13	17.80	3224	70	790
	14	17.92	3226	66	760
	15	18.19	3249	65	750
	16	18.04	3241	65	750
	17	17.94	3216	65	750
	18	18.19	3267	65	750
	19	17.88	3244	65	740
	20	18.04	3248	65	740
	21	18.42	3284	65	740
	22	17.78	3228	65	740
T-055433-1	01	6.75			
	02	6.63			
	03	6.75			
	04	6.63			
	05	6.82			
	06	7.01			
	07	7.01			



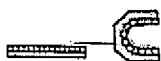
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6.0 FABRICATION ACTIVITIES



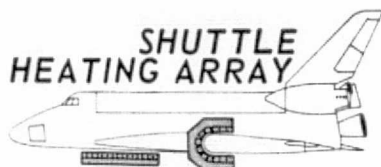
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6.0 FABRICATION ACTIVITIES

After considerable production planning, tooling design and fabrication, and material procurement, the actual fabrication of the heater array was begun. The water manifolds were designed to be made basically of two pieces of rectangular tubing capped at either end with either an angle or a flange plate, depending on the application of the particular manifold assembly. The first step in the manifold fabrication was to cut the rectangular tubing to length, weld in the water fittings and then straighten the tubes that became warped in the welding operation. The angle and plate ends which were made out of material thicker than need be to allow for stock removal, were prepared by machining to a flat surface, and then welded to the ends of the rectangular tubing. Subsequent to this welding operation, the assemblies went to the machine shop where they were machined square and also to equal length. The detail machining of the angle end of one of the manifolds is shown in Figure 58, while Figure 59 illustrates a facing operation on the flat end of a heater manifold. When the machining was completed on the manifold, the various mount holes for reflectors and other hardware, were drilled and tapped in the manifold using jigs for location to insure interchangeability of manifolds. This operation is shown in Figure 60. The completed manifolds were then degreased and sent to an outside vendor for electroless nickel plating to make them corrosion resistant.

The reflector design specified gold plated 1/8 inch copper plate with 1/4 inch copper cooling tubes soldered to the back side. The 1/8 inch copper plate was cut out, deburred, and its mounting holes jig drilled to insure a proper fit on the manifold assemblies. Following this operation, the copper plates were sent to a vendor for gold plating. The copper tube cooling coils were formed on special jigs with special benders, and checked for proper fit on a mockup assembly. This is illustrated in Figure 61. When the copper plates returned from the gold plating vendor, the completed cooling tubes were assembled to the plates using jigs and clamps, as shown in Figure 62. The application of solder and flux followed by a torch soldering operation and cleaning, completed the assembly of the reflectors.

All of the detailed machine parts were done in lots on a single setup to insure interchangeability with their holes being jig drilled and all brazing assembly also



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MACHINING OF HEATER MANIFOLD

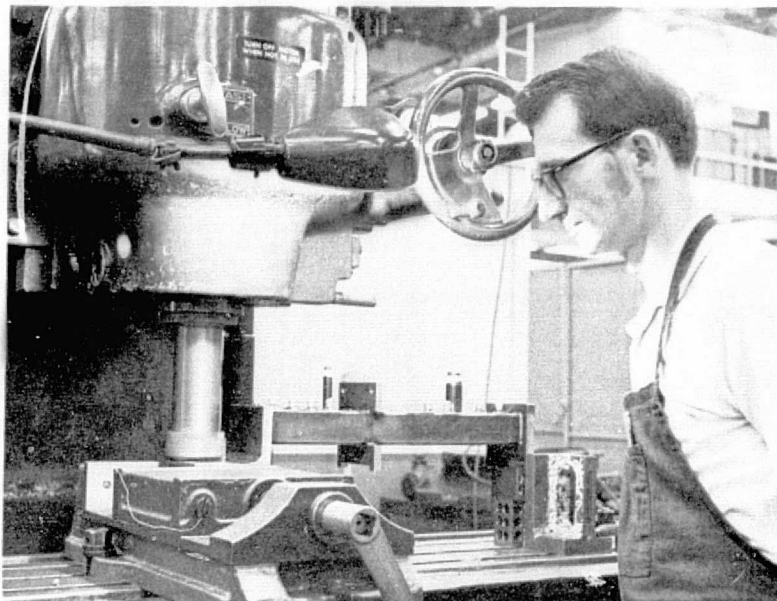


FIGURE 58

FACING OPERATION ON HEATER MANIFOLD

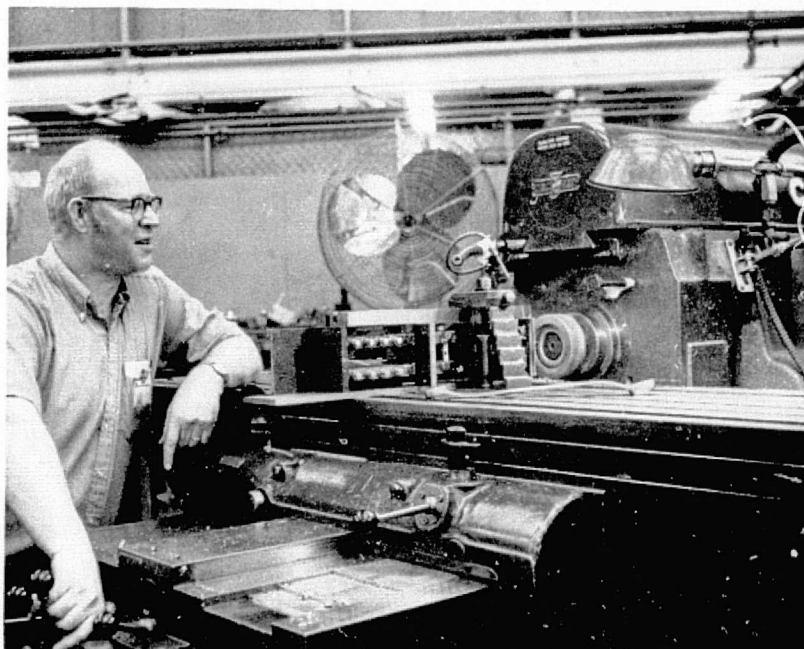
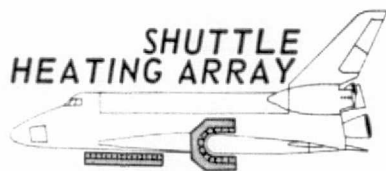


FIGURE 59



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DRILLING OF HEATER MANIFOLD FOR MOUNTING SIDE REFLECTORS

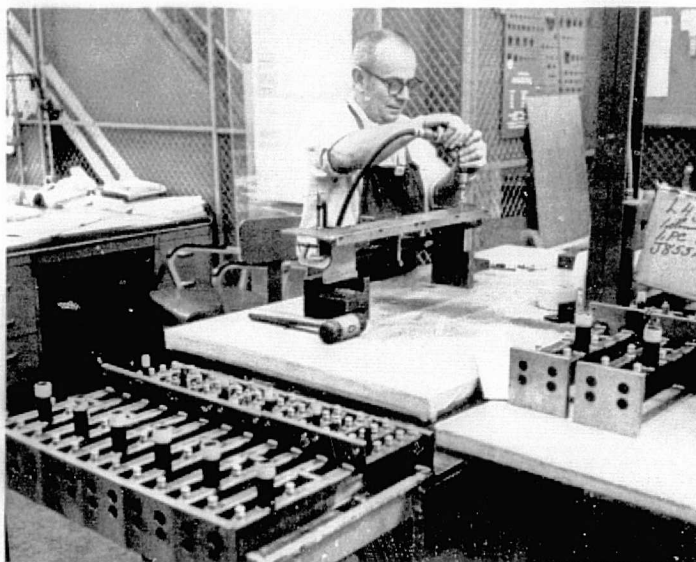


FIGURE 60

COOLANT TUBE FORMING

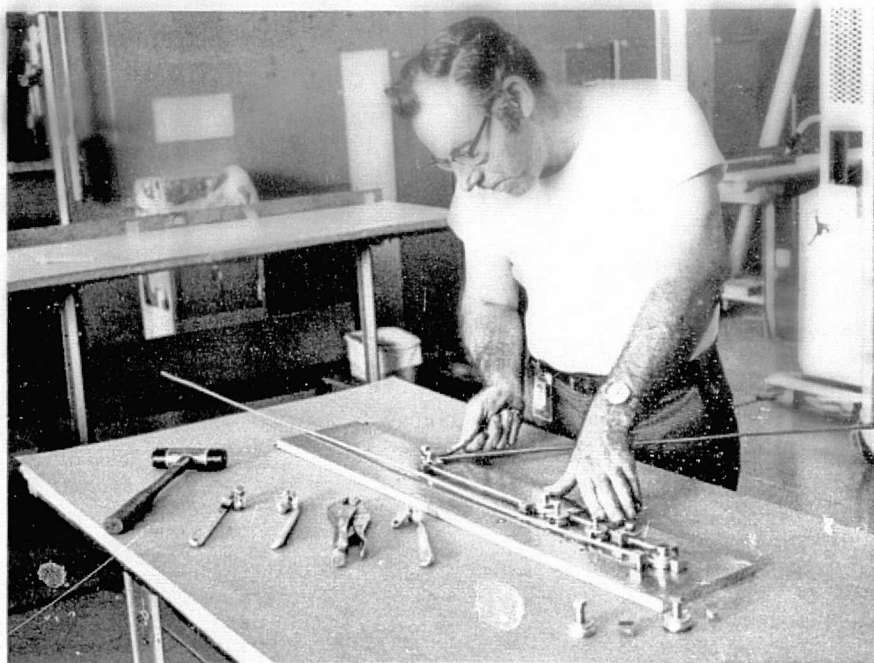
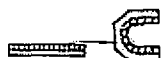


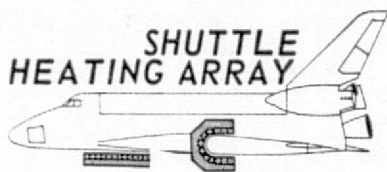
FIGURE 61



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being done in jigs to insure the commonality of parts. Following completion of the detailed machine parts, subassembly began, where the electrode ends and support ends were assembled into units. This subassembly procedure is illustrated in Figure 63. Final assembly consisted of mounting a reflector and subassembly end to the corresponding manifold, and finally bolting the sections together to form a complete heater assembly.

The design of the support structure called for this assembly to function both as a supporting member and as a water manifold and, also, to be readily configured to support a flat heating array or a leading edge heating array. The basic support structure was made up of two 4 inch diameter pipes with suitable interconnecting structure and flange supports for a pair of U-shaped manifolds to support the leading edge array. The entire structure was made from standard 4 inch pipe hardware including caps, elbows, flanges and straight sections of pipe. These sections were cut, fitted and welded to exacting tolerances for ease of changing from the leading edge array to the flat array. Figure 64 shows a partly assembled U-manifold during its fabrication while Figure 65 shows the partially completed base assembly of the support structure during fabrication. Figure 66 shows the hoisting brackets being welded to the support structure and also shows the support structure with the U-manifolds in place. Subsequent to all welding operations, the support structure was hydrostatically tested for leaks and structural integrity. To insure corrosion protection the completed support structure was sent to a vendor for internal nickel plating and painting external with solvent resistant polyurethane paint.



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ATTACHING COOLANT TUBES TO REFLECTOR S

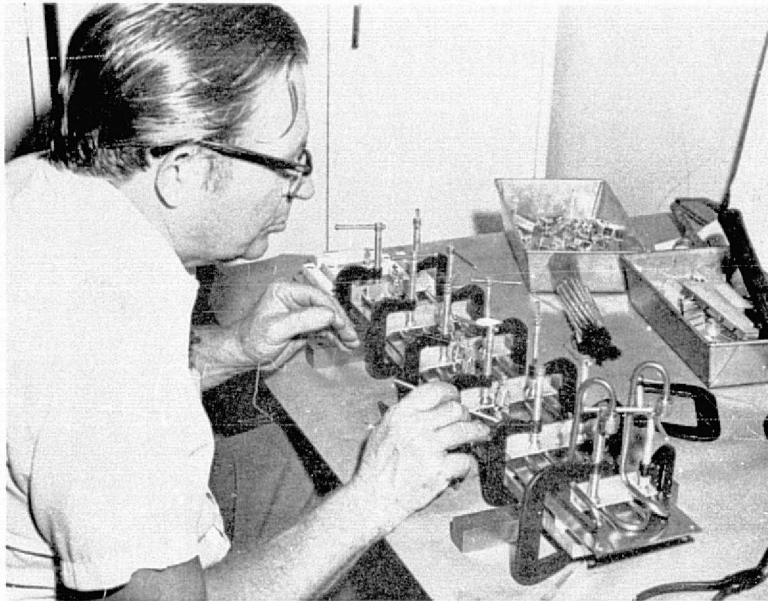
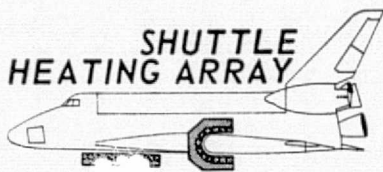


FIGURE 62

SUBASSEMBLY OF ELECTRODE DETAILS



FIGURE 63



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SUPPORT STRUCTURE "U" MANIFOLD DURING FABRICATION

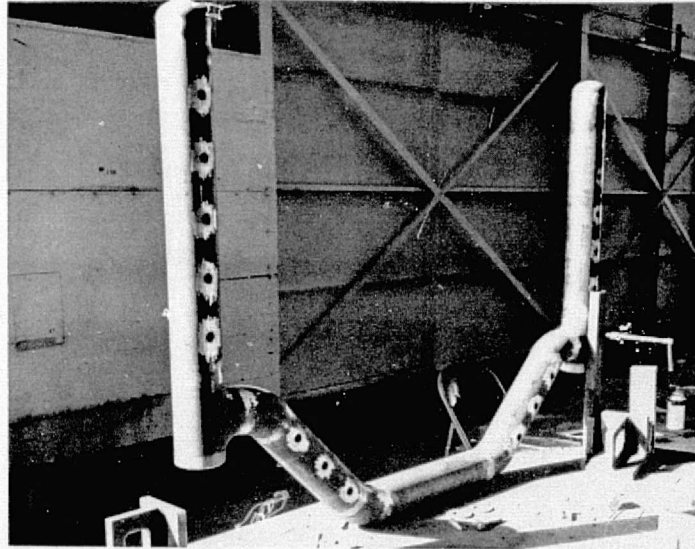


FIGURE 64

SUPPORT STRUCTURE DURING FABRICATION

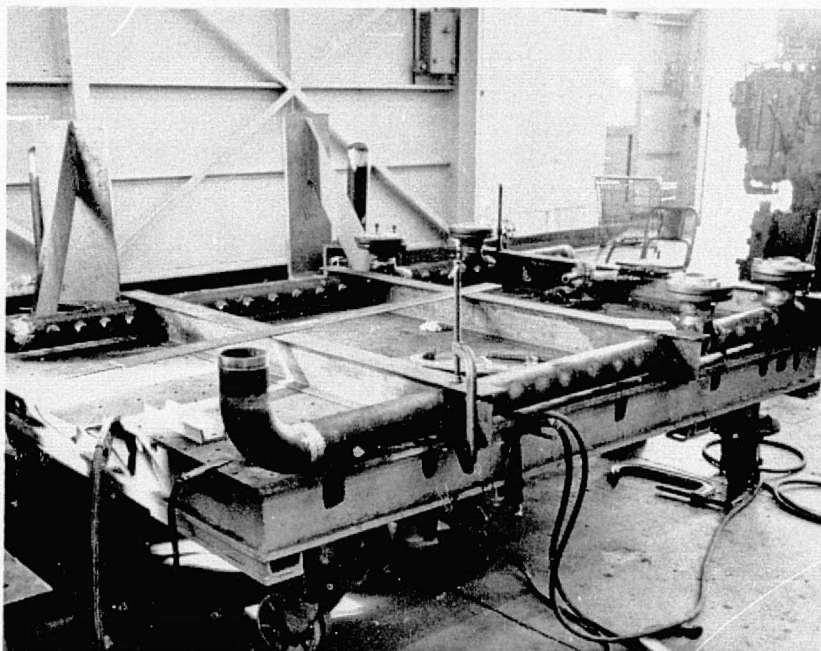
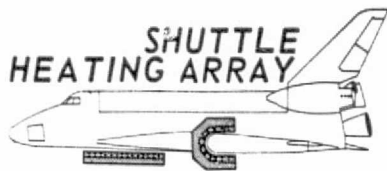


FIGURE 65



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WELDING OF HOISTING BRACKETS ON SUPPORT STRUCTURE

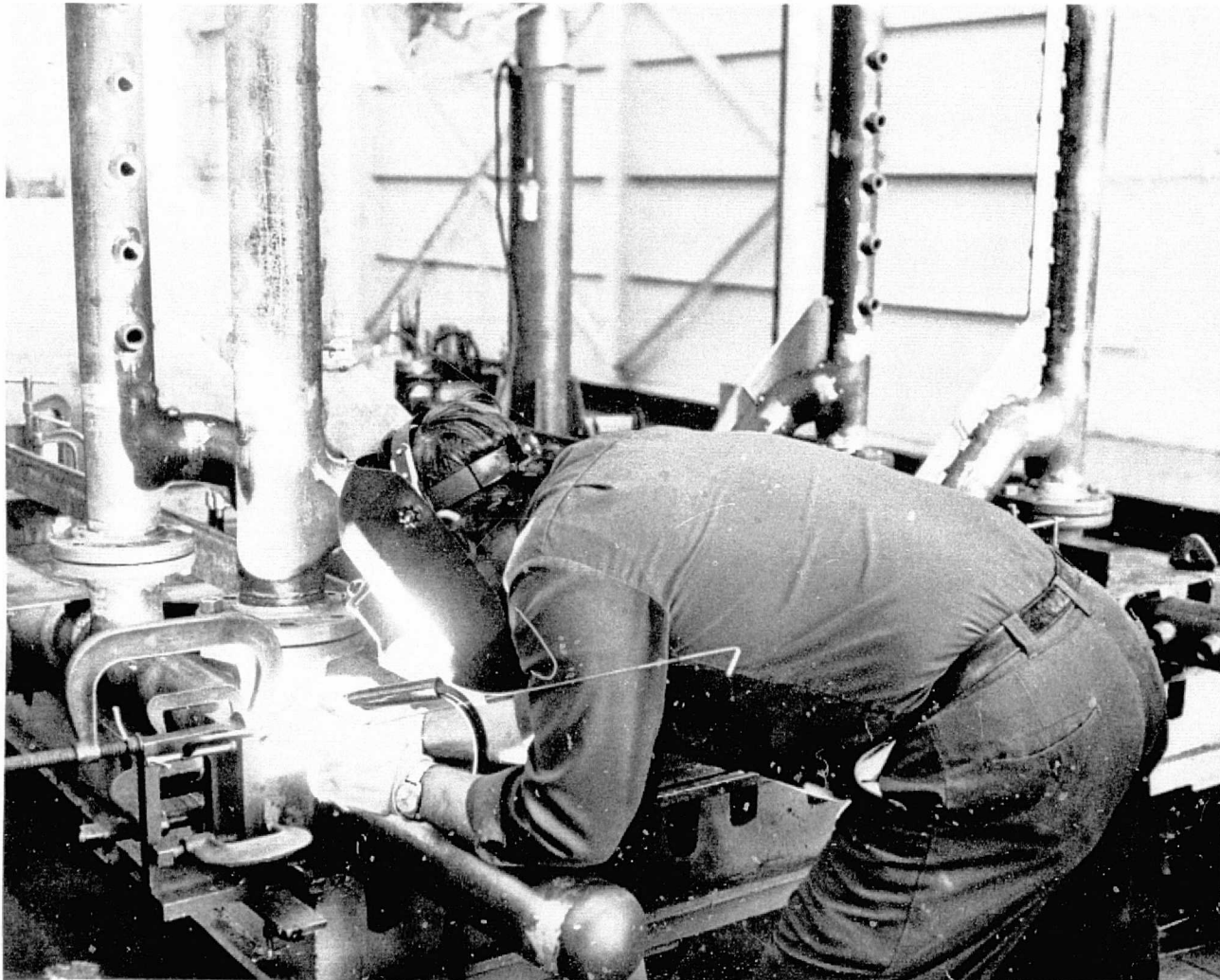
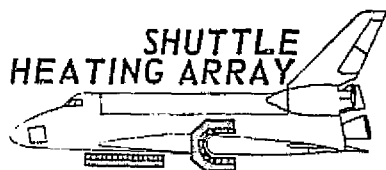


FIGURE 66



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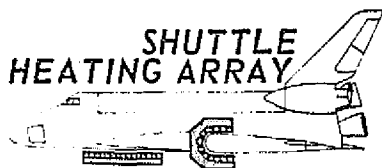
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7.0 ENGINEERING DRAWINGS

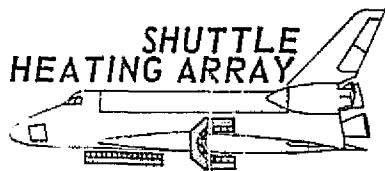
8.0 OPERATION, MAINTENANCE AND REPAIR MANUAL

**FINAL REPORT****7.0 ENGINEERING DRAWINGS**

The complete set of engineering drawings and specifications used to manufacture the heating arrays is contained in JSC Report 09491 (MDC Report E1233). These drawings and specifications were approved by the Contract Technical Monitor prior to fabrication of the array.

8.0 OPERATION, MAINTENANCE AND REPAIR MANUAL

A manual (JSC Report 09492, MDC Report E1234) describing correct operation, maintenance and repair of the Leading Edge/Flat Surface Heating Array was prepared and supplied with the array. The manual contains, a general description of the heating array and recommended auxiliary equipment, operation procedures, maintenance instructions, repair instructions, schematics, spare parts lists, and engineering drawings. The proper replacement of components, correct torque values, step by step maintenance instructions and installation array procedure along with pretest checkouts are described.



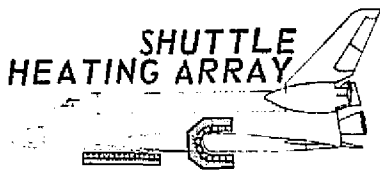
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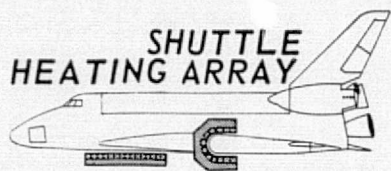
FINAL REPORT

9.0 INSTALLATION OF HEATING ARRAY AT JSC

**FINAL REPORT****9.0 HEATING ARRAY INSTALLATION AT JSC**

Concurrent with the fabrication of the heating array, NASA-JSC was assembling and checking out the other major components of the Radiant Heat Facility in Building 260. These components included; the 10 foot diameter vacuum chamber, vacuum pumping system, fluid coolant system, transformer bank, power controllers and other electrical equipment, inert gas system, computer system for recording test data and controlling the heating array, and drawer installation within the vacuum chamber. One of the final activities of this program was technical assistance to JSC personnel who installed the Heating Array in Building 260.

The support structure was fit to the drawer assembly and the coolant headers plumbed to the vacuum chamber pass-throughs. A heater module with its instrumentation and test article were installed next to checkout operation of the entire facility. A number of test runs were then performed before the remaining modules were sequentially installed and tested. Figure 67 contains several views of the heating array during its installation.



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INSTALLATION OF HEATING ARRAY AT JSC

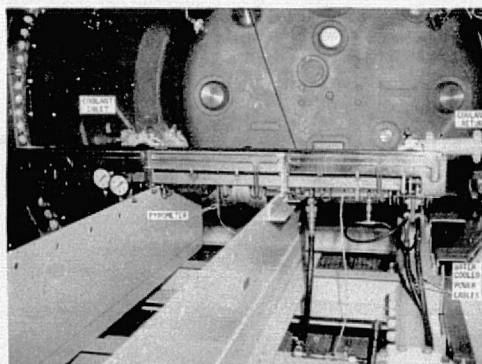
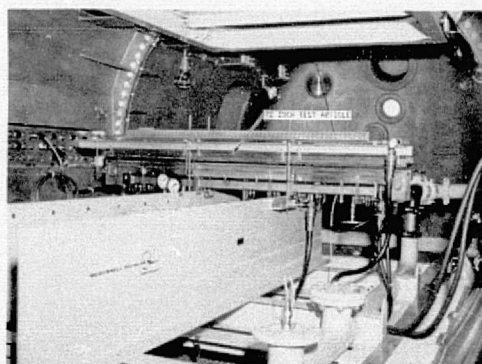
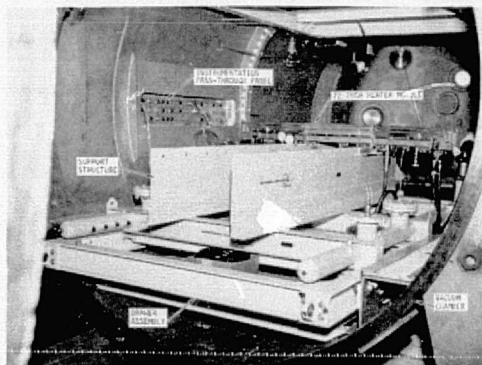


FIGURE 67



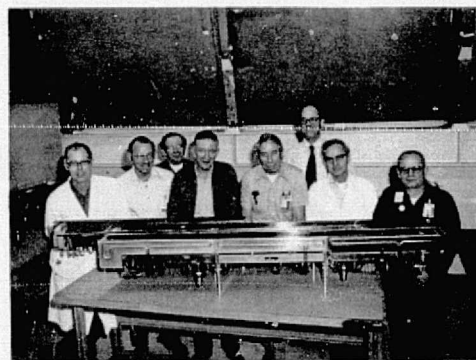
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ACKNOWLEDGEMENT

Many components of the McDonnell Douglas Corporation contributed to the successful design, fabrication and delivery of the Leading Edge/Flat Heating Array. This was possible because of the talents and skills of individuals within the McDonnell Douglas team. This was further evident by the personal pride and attention to detail throughout the program from the conceptual design design and analyses, system development tests, final design, scheduling, material procurement, coordination, part fabrication, sub-assembly, final assembly, system checkout, functional acceptance test, shipping, and culminating with the coordination of array installation at NASA-JSC. I would like to thank all who contributed to the project.



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